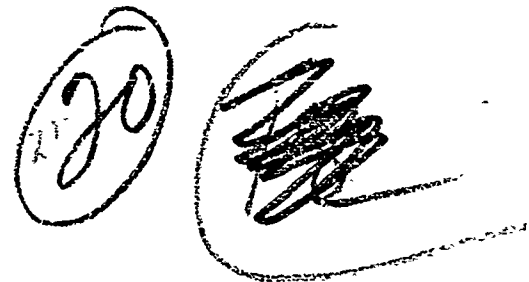


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AFML-TR-70-58
Volume I



AD878220

**ADVANCED COMPOSITES DATA
FOR
AIRCRAFT STRUCTURAL DESIGN**

**Volume I: Material and Basic
Allowable Development -
Boron/Epoxy**

L. M. Lackman
G. R. Arvin
E. O. Dickerson
R. B. Meadows

**LOS ANGELES DIVISION
NORTH AMERICAN ROCKWELL**



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TECHNICAL REPORT AFML-TR-70-58, VOLUME I

AUGUST 1970

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FOREWORD

This report was prepared by the Los Angeles Division of North American Rockwell Corporation under Contract F33615-68-C-1489, Project 6169CW, for the Advanced Composites Division, Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. Mr. R. L. Rapson (AFML/LC) was the Air Force Project Engineer and Dr. L. M. Lackman was the North American Rockwell Program Manager. The work described in this report was performed during the period from 15 March 1968 to 15 December 1969.


The authors of Volume I are Dr. L. M. Lackman, and Messrs. G. H. Arvin, E. O. Dickerson, and R. B. Meadows, who were responsible in the course of this program for program management and analytical studies, structural design manual development, experimental testing and data reduction, and specimen fabrication, respectively. In addition, Mr. Arvin also served as the General Editor of this report.

That portion of the basic allowable determination pertaining to the effect of nuclear blasts was assigned to the Columbus Division of North American Rockwell. Mr. K. I. Clayton was responsible for this segment of the program and for the corresponding subsection of this report. Dr. A. Caputo contributed to the thermal expansion analysis described in Section V.

The authors wish to acknowledge the contribution of the Fort Worth Division of General Dynamics to this program, in particular for their assistance during the material development phase and in general for the smooth coordination between this program and their related concurrent efforts under Contract F33615-68-C-1474. Special mention is made in these regards for the cooperation and assistance of Mr. P. D. Shockey.

This report was submitted by the authors 3 March 1970.

This technical report has been reviewed and is approved.


Robert C. Tomashot
Technical Area Manager
Advanced Composites Division

ABSTRACT

This volume is Volume I of four volumes and summarizes that portion of the program under Contract F33615-69-C-1489 concerned with the development of a material processing technology at NR, the determination of material properties for a specific epoxy resin and glass scrim cloth, the determination of the effects of nuclear blast on the strength of a composite laminate, and the assessment of existing micromechanics techniques for the prediction of composite lamina characteristics. All efforts in this program were relative to a specific boron/epoxy composite material system, known commercially as Narmco Rigidite 5505, produced in prepreg form by the Narmco Materials Division of the Whittaker Corporation.

During the material and processing development, a procurement specification (Appendix I) and a process specification (Appendix II) were established, and have demonstrated a capability to produce satisfactory material consistently, provided the prepreg tape used is of high quality. Prepreg tape made with twisted filaments or with too advanced a resin is shown to be unacceptable. A concept of prepreg tape with rotated scrim cloth is shown to increase certain mechanical properties markedly.

Tests are described for a program to characterize individually Narmco 2387 resin (the matrix resin in Narmco 5505 composite) and 104 glass scrim cloth. Test data are presented for standard mechanical properties and elastic constants at room temperature and 350°F.

A test program to determine the effects of nuclear blast on boron/epoxy laminates is described and test data are presented. The effects of nuclear radiation as studied under this program were shown to be of no practical concern in aerospace structure design, but thermal shock effects can be significantly damaging without adequate thermal protection.

An evaluation is presented to show the degree of validity of several existing micromechanics techniques for predicting composite lamina characteristics from known properties of the constituents. Elastic constants and thermal coefficients of expansion are presented, and predicted properties are compared to test results. A separate assessment is made of macromechanics techniques for predicting the coefficients of expansion of a crossplied laminate.

This abstract is subject to special export controls, and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Air Force Materials Laboratory, (AFML/LC), Wright-Patterson Air Force Base, Ohio 45433.

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LIST OF SYMBOLS

A	- area (in. ²)
a	- length dimension (in.), esp rectangular panel
b	- width dimension (in.) esp width of compression panel normal to load, or breadth of beam cross section
C _L	- centerline
D	- diameter (in.)
E	- Young's modulus (lb/in. ²)
E _f	- Young's modulus of filament material (lb/in. ²)
E _m	- Young's modulus of matrix material (lb/in. ²)
E _L ^g	- Young's modulus of impregnated glass scrim cloth in filament direction (lb/in. ²)
E _T ^g	- Young's modulus of impregnated glass scrim cloth transverse to filament direction (lb/in. ²)
E _L , E _α	- Young's modulus of laminae parallel to filament direction (lb/in. ²)
E _T , E _β	- Young's modulus of laminae transverse to filament direction (lb/in. ²)
E _x	- Young's modulus of laminate along X reference axis (lb/in. ²)
E _y	- Young's modulus of laminate along Y reference axis (lb/in. ²)
F	- allowable stress (lb/in. ²)
f	- applied stress (lb/in. ²)
G	- shear modulus
G _f	- shear modulus of filament material (lb/in. ²)
G _m	- shear modulus of matrix material (lb/in. ²)

G_{LT}^g	- shear modulus of impregnated glass scrim cloth (lb/in. ²)
$G_{LT}, G_{\alpha\beta}$	- shear modulus of laminae in LT or $\alpha\beta$ plane (lb/in. ²)
G_{xy}	- shear modulus of laminate in XY reference plane (lb/in. ²)
h	- height dimension (in.), esp height of beam cross section. Also, sometimes used for thickness.
h_i	- thickness of i^{th} ply or lamina (in.)
M	- moment (in.-lb)
P	- applied load (lb)
t	- (1) thickness (in.) - (2) time (sec)
V_f	- filament content (% by volume)
V_g	- glass scrim cloth content (% by volume)
V_m	- matrix content (% by volume)
α	- coefficient of thermal expansion (in./in./°F)
α_f	- coefficient of thermal expansion for filament material (in./in./°F)
α_m	- coefficient of thermal expansion for matrix material (in./in./°F)
α_L^g	- coefficient of thermal expansion of impregnated scrim cloth in filament direction (in./in./°F)
α_T^g	- coefficient of thermal expansion of impregnated scrim cloth transverse to filament direction (in./in./°F)
α_L, α_α	- laminae coefficient of thermal expansion along L or α axis (in./in./°F)
α_T, α_β	- laminae coefficient of thermal expansion along T or β axis (in./in./°F)
α_x	- laminate coefficient of thermal expansion along general reference X axis (in./in./°F)

α_Y	- laminate coefficient of thermal expansion along general reference Y axis (in./in./°F)
α_{xy}	- laminate shear distortion coefficient of thermal expansion (in./in./°F)
Δ	- difference (used as prefix to quantitative symbols)
δ	- elongation or deflection (in.)
ϵ	- strain (in./in.)
γ	- shear strain (in./in.)
θ	- angular orientation of a lamina in a laminate, i.e., angle between L and X axes (°)
ν	- Poisson's ratio
ν_f	- Poisson's ratio of filament material
ν_m	- Poisson's ratio of matrix material
ν_{LT}^g	- glass scrim cloth Poisson's ratio relating to contraction in the transverse direction due to extension in the longitudinal direction
ν_{TL}^g	- glass scrim cloth Poisson's ratio relating to contraction in the longitudinal direction due to extension in the transverse direction
$\nu_{LT}, \nu_{\alpha\beta}$	- Poisson's ratio relating contraction in the T or β direction due to extension in the L or α direction
$\nu_{TL}, \nu_{\beta\alpha}$	- Poisson's ratio relating contraction in the L or α direction due to extension in the T or β direction
ν_{xy}	- Poisson's ratio relating contraction in the y direction due to extension in the x direction
ν_{yx}	- Poisson's ratio relating contraction in the x direction due to extension in the y direction
Σ	- total
σ	- applied axial stress (lb/in. ²)
τ	- applied shear stress (lb/in. ²)

SUBSCRIPTS

c	- composite or laminate as a whole, as distinguished from individual constituents
f	- filament
g	- glass scrim cloth
i	- i^{th} position in a sequence
L, T, z	- laminae natural orthogonal coordinates
m	- matrix
max	- maximum
min	- minimum
x, y, z	- general coordinate system, also laminate coordinate system.
α, β, z	- laminae natural orthogonal coordinates
Σ	- total
0	- initial or reference datum

SUPERSCRIPTS

c	- (1) compression or creep - (2) composite or laminate as a whole, as distinguished from individual constituents
cu	- compression ultimate
f	- filament
g	- glass scrim cloth
is	- interlaminar shear
isu	- interlaminar shear ultimate
m	- matrix

pl	- proportional limit
s	- shear
su	- shear ultimate
t	- tension
tu	- tension ultimate
<u> </u> (overline)	- denotes parameter related to portion of composite lamina exclusive of scrim cloth

UNITS OF MEASUREMENT

Ksi	- Kilopounds per square inch, 10^3 lb/in. ²
Msi	- Megapounds per square inch, 10^6 lb/in. ²
n	- neutrons
r	- Roentgens
μ	- prefix micro- (10^{-6})
G	- prefix Giga- (10^9)
T	- prefix Tera- (10^{12})
KT	- prefix Kilo-Tera- (10^{15})
MT	- prefix Mega-Tera- (10^{18})

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Section I

INTRODUCTION

The purpose of this program was to take the first step toward the generation and presentation of basic engineering data necessary to perform high-confidence-level structural design of primary aircraft structures utilizing advanced composite materials. The program was limited to an in-depth generation of basic material allowables for one boron/epoxy and several graphite/epoxy material systems, and the determination of basic structural element response for the boron/epoxy system alone. The boron portion of this program was conducted in conjunction with a concurrent General Dynamics/Fort Worth (GD/FW) program which was funded under Air Force Contract F33615-68-C-1474. The boron/epoxy material system highlighted by both these programs was Narmco 5505, furnished by the supplier as 3-inch prepreg tape. This is a composite material consisting of collimated 4-mil boron filaments, 208 per inch of tape width, embedded in a matrix of Narmco 2387 epoxy resin, and supported on a 1-mil layer of 104 glass scrim cloth. The graphite portion of this program is being conducted independent of any other program, and will be described in fuller detail in a later volume of this report. Additional data for all these materials, as well as for other filament/matrix material systems, were obtained from published Government, industry, and technical journal reports, and were used to augment the data generated in this program.

This program was composed of three major work task areas:

- Task I - Generation of Composite Material Design Allowables
- Task II - Structural Element Test Program and Analysis Evaluation
- Task III - Development of Advanced Composite Structural Design Manual for Aircraft

Task I is divided into two distinct areas of effort by the separate boron/epoxy and graphite/epoxy programs. The purpose of the boron portion of task I was to complement the basic material design allowable activities conducted by GD/FW (reference 12) and to develop acceptable laminate fabrication and inspection procedures. The boron effort was divided into the following work areas: The establishment of program coordination procedures for the North American Rockwell Corporation and General Dynamics related programs; the accomplishment of a limited material development program; the generation of basic allowables for the constituent materials; establishment of the accuracy of current analytical procedures for predicting certain basic allowables; and the development, where reliable techniques were lacking, of prediction techniques for these basic material allowables.

The graphite portion of task I consists primarily of a screening and characterization of several graphite/epoxy material systems and will be delineated in a later volume of this report.

The purpose of task II, which was concerned solely with boron/epoxy material, was to generate data on basic structural elements which form the building blocks from which aircraft structures are designed. A minimum evaluation of structural elements was conducted, including one basic laminate and one elevated temperature. Factors which were considered in the detail design of the structural elements included laminate orientations, panel proportions and edge restraints, effectiveness of typical forms of panel stabilization, evaluation of cutouts, and thermal gradient effects. One or more elements were selected for each primary and/or combined load applications. The test program included local and general instability of flat panels and natural frequency determinations. The results of this test program were compared to predicted response, failure mode, and strength techniques for basic structural elements.

The task III work area was originally centered on the development of an advanced composite structural design manual for aircraft structures. The first effort of this task involved revision and refinement of the Aircraft Division of the Intermediate Draft of the Structural Design Guide developed by the Southwest Research Institute, San Antonio, Texas, under Air Force Contract AF33(615)-5142. The completely revised and reorganized Aircraft Division resulting from this phase of effort was published in the Final Draft of the Design Guide in November 1968 under Contract AF33(615)-68-C-1241. Soon thereafter, a review of the Final Draft by a select industry group led to a decision by AFML to reorganize the entire Design Guide for the First Edition, which was then assigned to NR/LAD under Contract F33615-69-C-1368.

Subsequent phases of task III of this program, in light of the foregoing developments, consisted of the preparation of the Aircraft System Applications chapter of the First Edition of the Design Guide as well as the preparation of data generated by tasks I and II of this program for incorporation into the various technical function-oriented chapters. Task III also included the incorporation into the Design Guide of data generated by the concurrent GD program.

The bulk of the basic material allowables for the 5505 material system was generated by the General Dynamics contract. This concurrent and integrally related contract was coordinated with the Los Angeles Division program effort through scheduled periodic coordination meetings. These meetings insured the continuous flow of pertinent program data between the two contractors.

This report is divided into four separate volumes, in each of which the subject areas of interest comprise an independent segment of the overall program. Each volume is a self-contained document, complementing the other

three volumes but not dependent upon them for coherence or continuity. The titles of the four volumes are:

- Volume I - Material and Basic Allowable Development - Boron/Epoxy
- Volume II - Structural Element Behavior - Test and Analytical Determination
- Volume III - Theoretical Methods
- Volume IV - Material and Basic Allowable Development - Graphite/Epoxy

Volume I contains three major areas of interest: The material development program (section III), the basic allowable program (section IV), and an evaluation of micromechanics prediction techniques (section V).

Section III covers the history of the problems encountered in quality control of supplier-fabricated prepreg tape, the fabrication and test program to demonstrate the quality and consistency of NR-fabricated laminates, and a NR-developed technique for augmenting the transverse properties of uniaxial laminae by reorienting the major axis of the scrim cloth.

Section IV covers the determination of mechanical properties of the resin matrix and scrim cloth constituents of Narmco 5505 boron/epoxy composite. The properties of the boron filament constituent were considered to be sufficiently established outside the efforts of this program. The properties of the fabricated Narmco 5505 composite itself, as distinguished from those of the individual constituents, were determined principally by General Dynamics. The one exception to the foregoing division of responsibilities is the NR-conducted investigation of nuclear blast effects on the mechanical properties of composite laminates, which is covered in section IV.

Section V is concerned with the assessment of existing techniques for elastic constants and thermal expansion characteristics of laminae as a function of constituent properties. In addition, a subsection concerning macromechanical prediction techniques for thermal expansion has been included here because of a desired continuity with the related micromechanics subsection.

Laminate ply orientations are described and specified in this report by use of the laminate orientation code defined in the Structural Design Guide for Advanced Composite Applications.

SECTION II

NR/GD COORDINATION

This program and the concurrent General Dynamics/Fort Worth Contract F33615-68-C-1474, entitled "Development of Engineering Data for Advanced Composite Materials," were mutually complementary. The basic interface between the two programs lay in those areas of each program related to the characterization of Narmco 5505 boron/epoxy composite in which NR had responsibility for determining the mechanical properties of the composite constituents; GD had responsibility for establishing mechanical and physical properties of the composite itself in several mutually agreed-upon "standard" laminate orientations; and NR, in turn, was responsible for determining the quantitative response characteristics of composite basic structural elements when subjected to various types of loading.

Consequently, continuous coordination between the two programs was conducted throughout their active spans. This was accomplished partly by a series of joint meetings of the NR and GD Program Managers and the AFML Project Engineer, held as circumstances dictated at either Wright Patterson AFB, Ohio, Fort Worth, or Los Angeles. Otherwise, continuous coordination was maintained by telephone and mail.

SECTION III

MATERIAL DEVELOPMENT PROGRAM

In this program, boron/epoxy fabrication technology was developed at NR initially through the use of General Dynamics (GD) material and process specifications and with the assistance of GD materials engineers. This technical base was expanded through the development of NR procurement and process specifications (appendixes I and II) and a quality control test fixture shown in figures 1 and 2.

The purpose of the material development task was to develop a materials technology base that would insure that all structural elements fabricated during this program would be of consistent high quality. The initial step consisted of fabricating 15-ply, 3- x 12-inch unidirectional quality-control-type panels from which longitudinal and transverse flexural specimens and interlaminar shear specimens were obtained and tested. Consistency in fabrication techniques was established almost immediately, and a quality verification program was initiated.

All boron/epoxy prepreg material was obtained from Narmco Materials Division of the Whittaker Corp in Costa Mesa, California, in the form of 3-inch-wide prepreg tape on rolls containing 250 to 300 continuous lineal feet of material, commercially known as Narmco Rigidite 5505. Laid-up composites were fabricated by curing for 2 hours at 350° F and 85 psi, initially as specified by GD/FW FPS 2001A and later in accordance with the NR-developed process specification (appendix II). All composite panels were laid up with the integral 104 glass scrim ply down. A separate 104 glass prepreg ply was used to close out the part and is referred to as a balance ply.

QUALITY CONTROL

Prepreg tape material received was inspected visually, and measurements were made to determine conformance of both physical and mechanical properties to the requirements of NR Specification ST0130LB0004 (appendix I). This specification requires the physical and mechanical properties shown in table I.

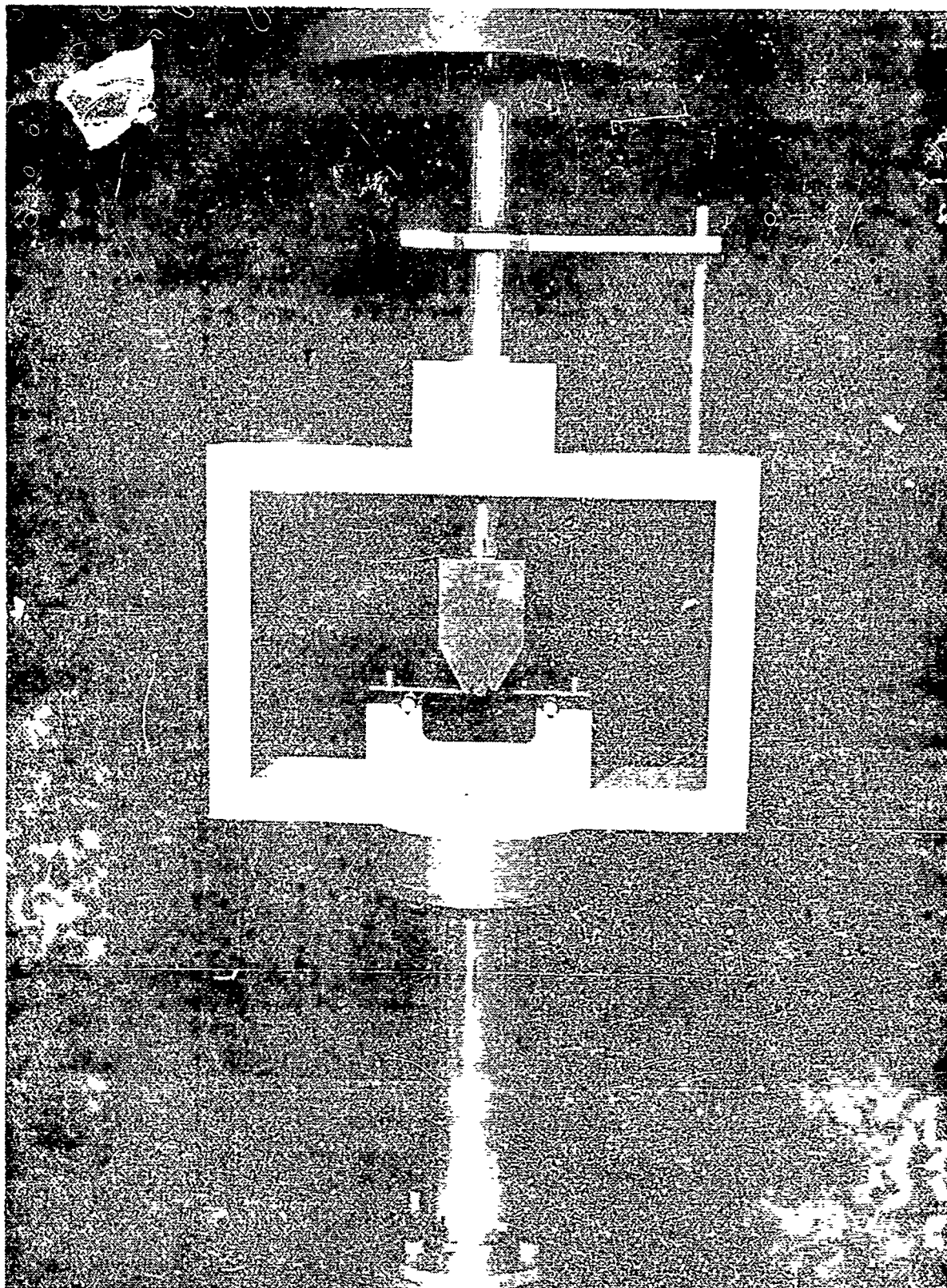
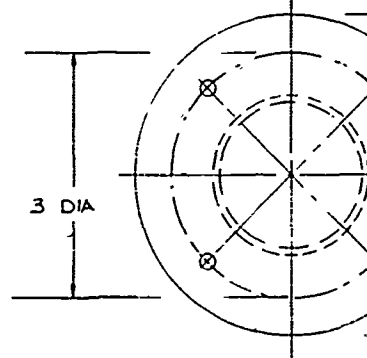
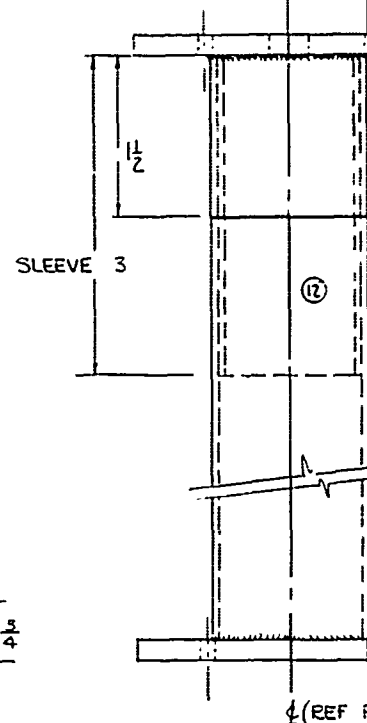
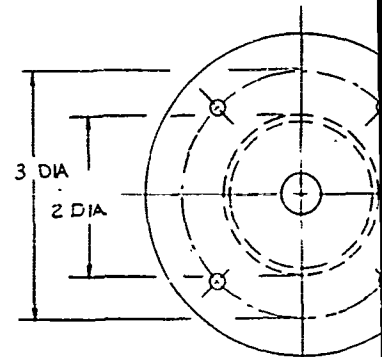
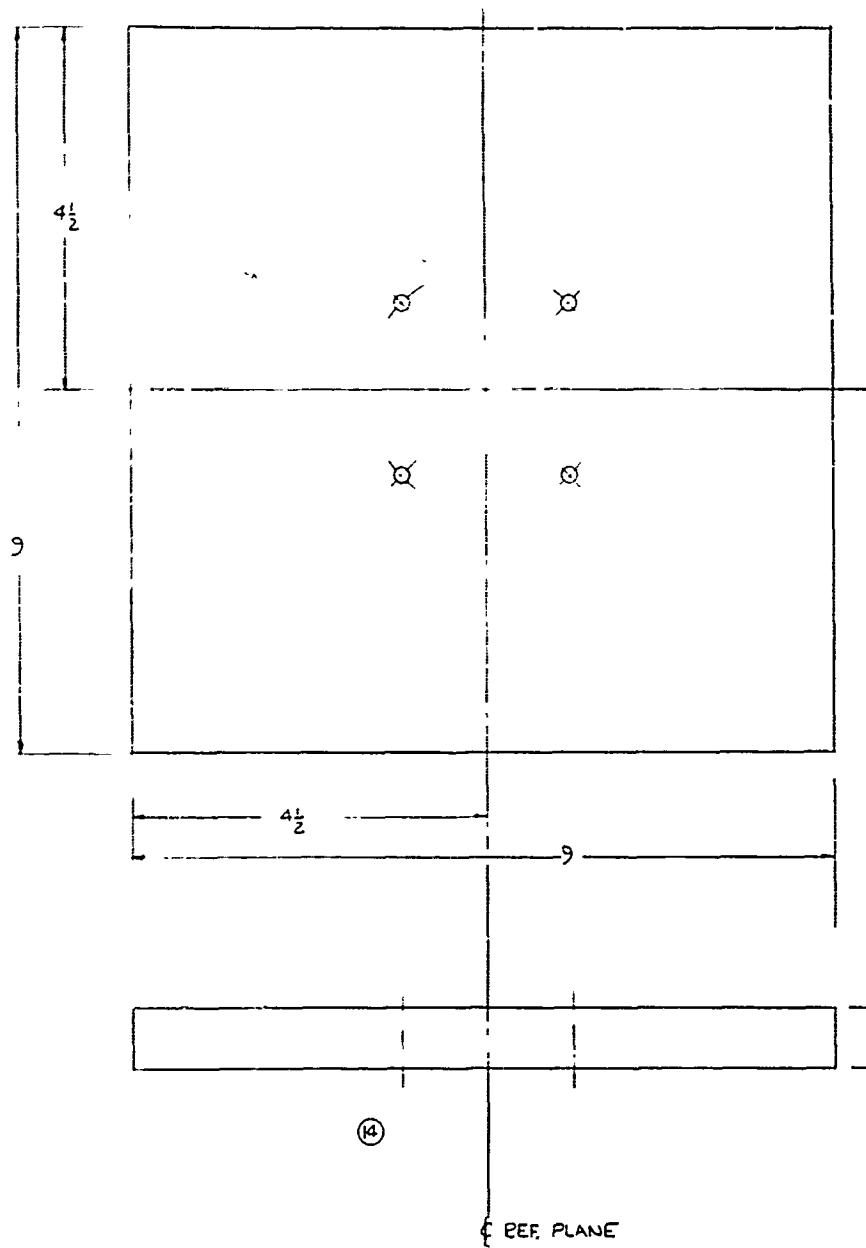
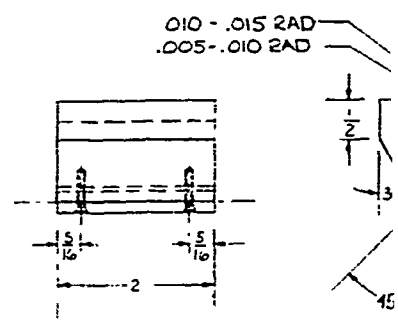
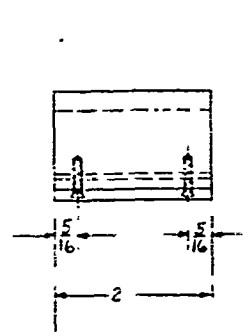
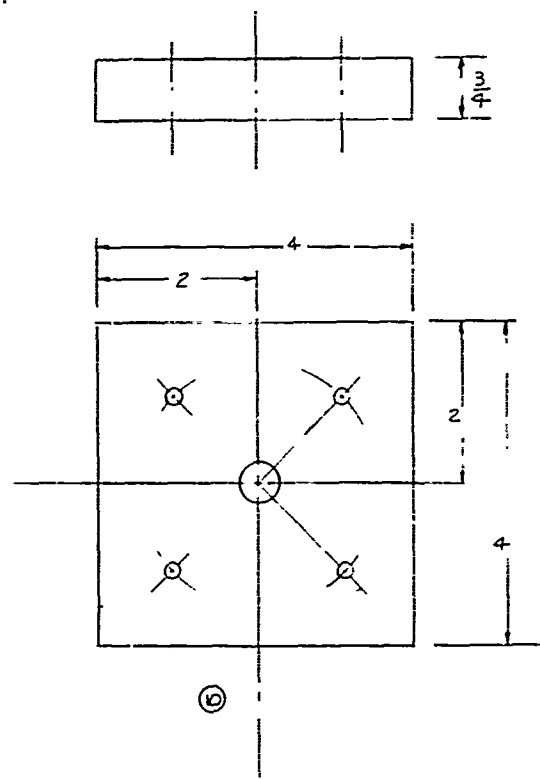
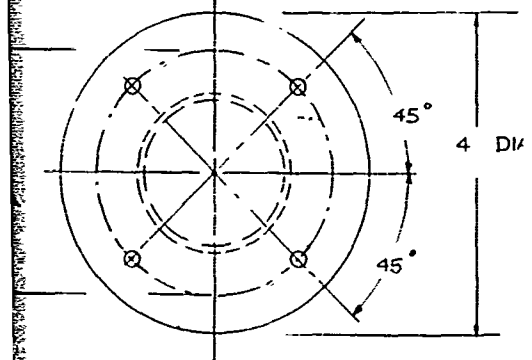
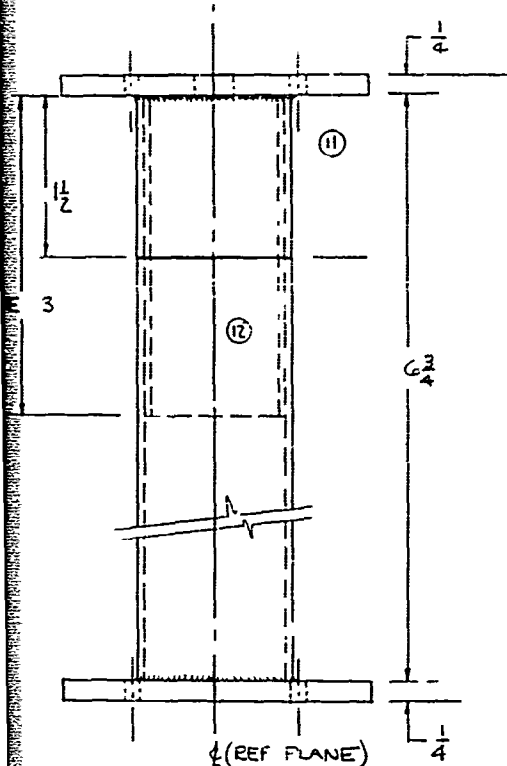
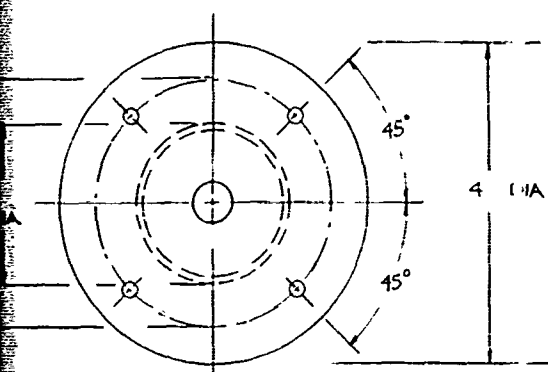


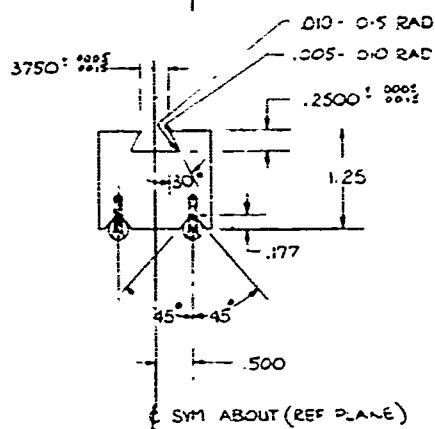
Figure 1. Quality Control test Fixture (Flexure and Interference Section)



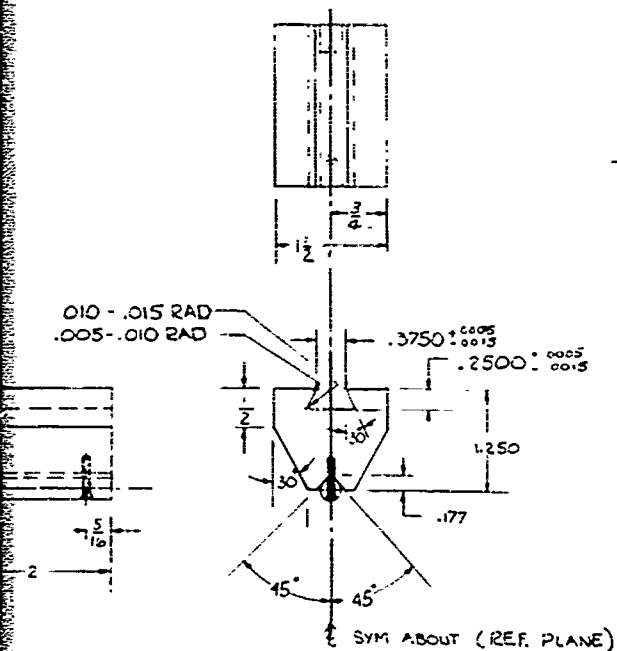
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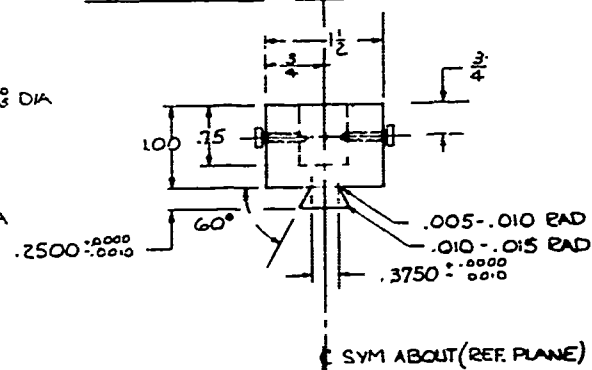
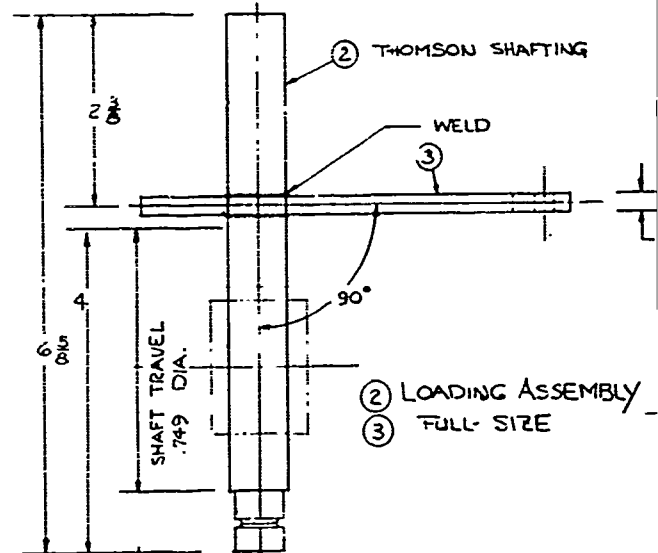
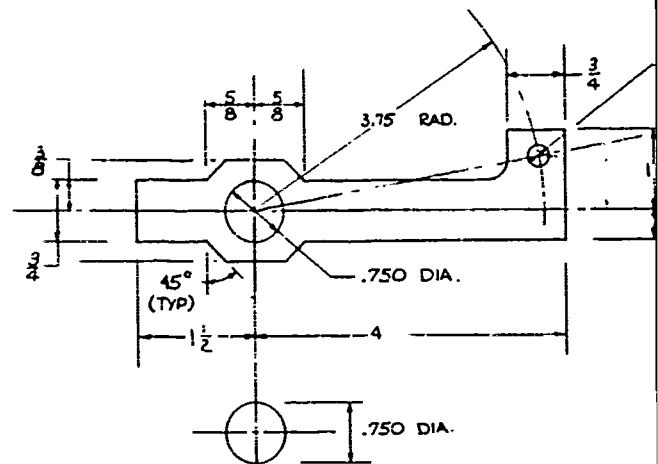
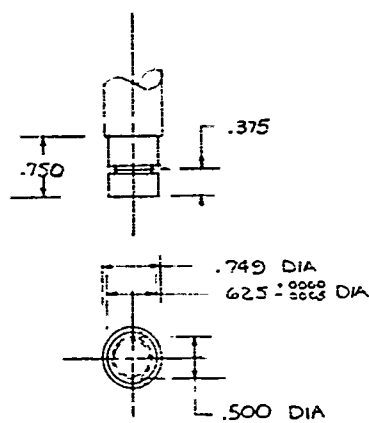
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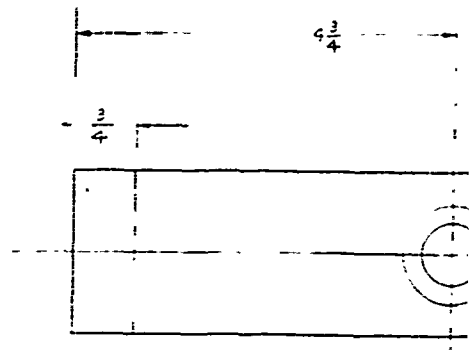
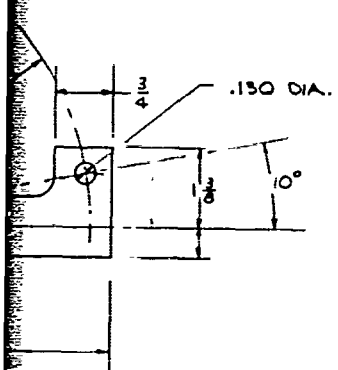
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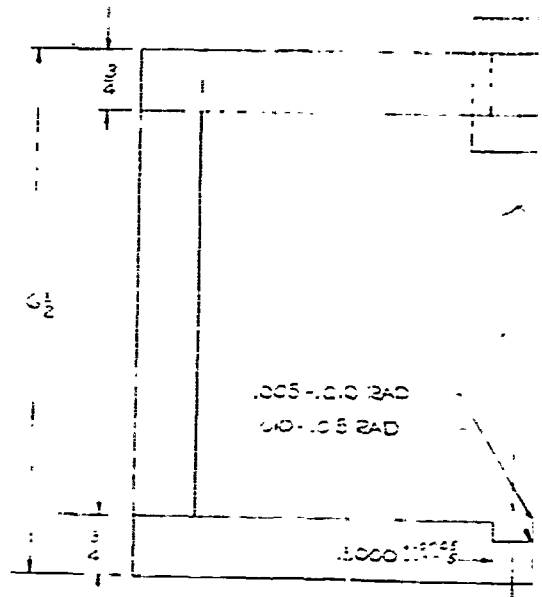
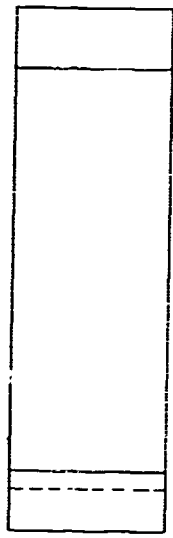
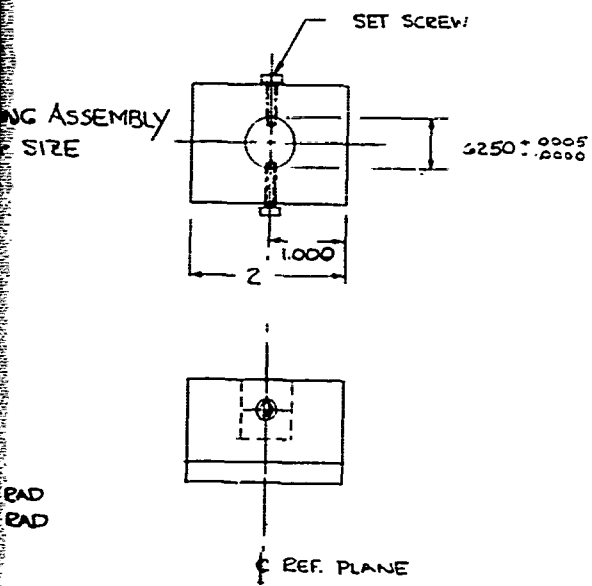
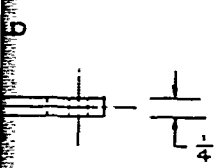
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④ UPPER LOADING HEAD
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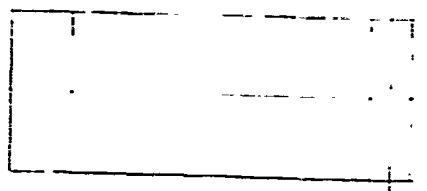
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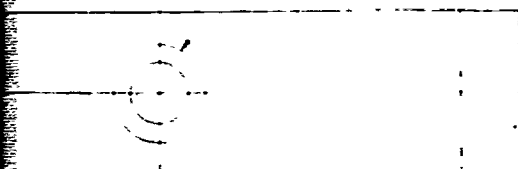
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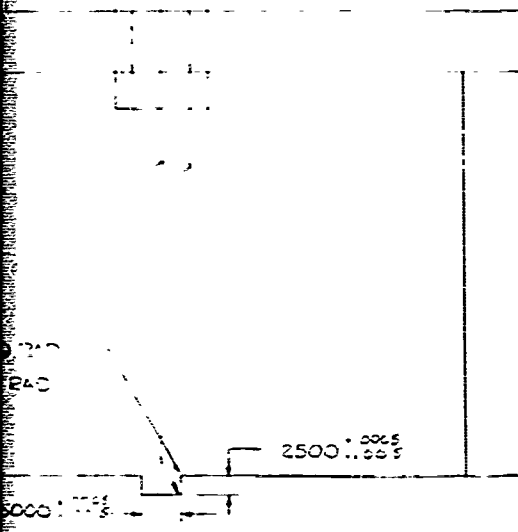
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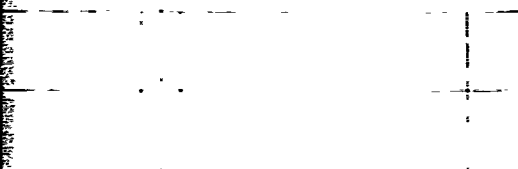
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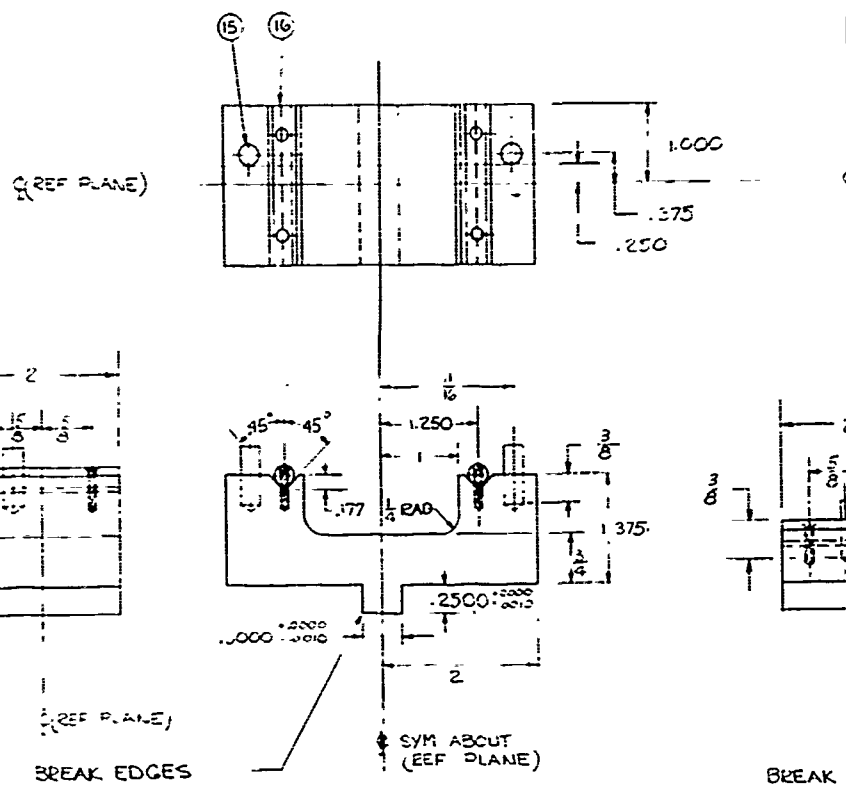
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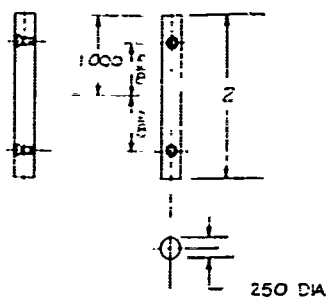


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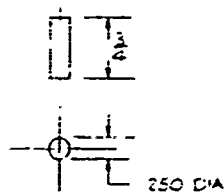


⑨ LOWER REACTION LOAD FIXTURE
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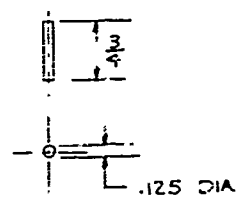
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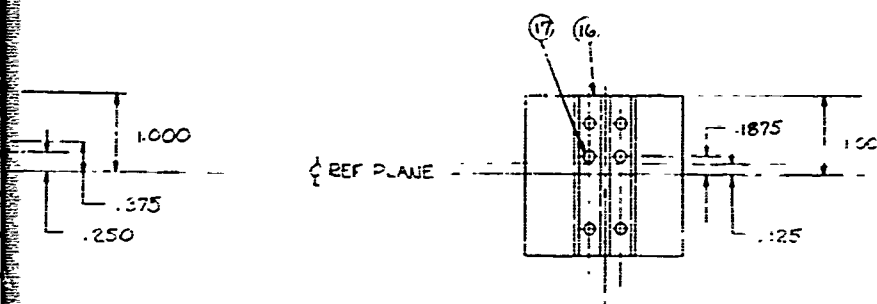
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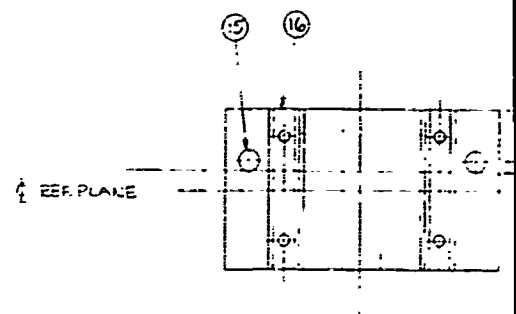
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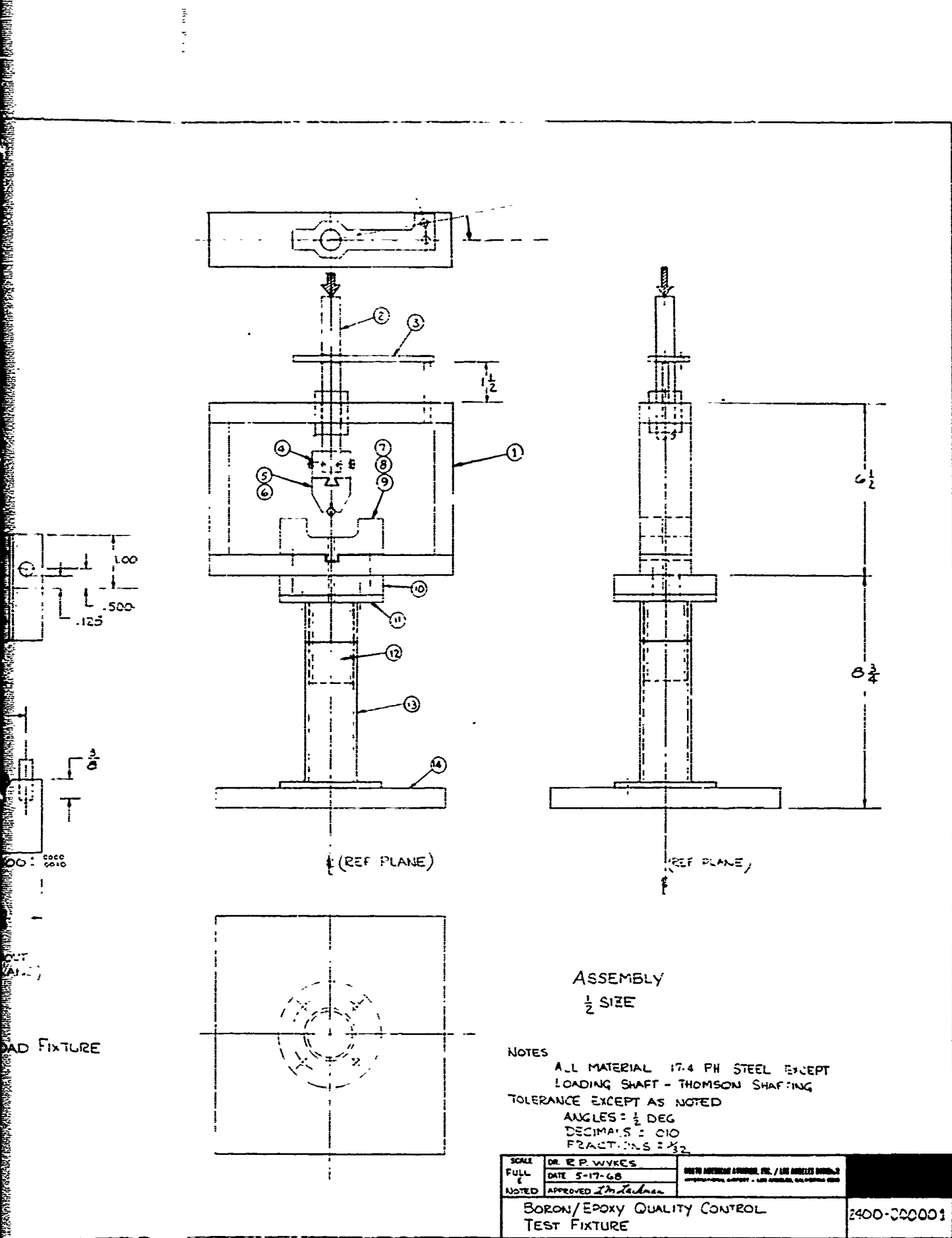


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⑦ LOWER REACTION LOAD FIXTURE
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TABLE I. MECHANICAL AND PHYSICAL PROPERTY
REQUIREMENTS OF ST0130LB0004

MECHANICAL PROPERTY REQUIREMENTS ⁽¹⁾

Test	RT	270° F	350° F
Longitudinal flexure (ksi)	225	195	170
Transverse flexure (ksi)	13	10	8
Interlaminar shear (ksi)	13	7	5

(1) Based on 15-ply unidirectional composite with a thickness per ply of 0.0051 inch minimum to 0.0054 inch maximum.

PHYSICAL PROPERTY REQUIREMENTS

Resin content	29 to 34 percent by weight
Volatile content	2 percent maximum
Tack	Adhere to a vertical steel surface
Flow ⁽²⁾	To be defined

(2) At present, flow shall be such as to produce a composite within a 0.0051- to 0.0054-inch per ply thickness when processed per ST0105LA0007.

The following paragraphs present the quality control results from each batch of prepreg tape received and the material problems encountered.

NARMCO 5505 - BATCH 283 (TEXACO FILAMENT)

The prepregging and quality control work performed by Narmco at their Costa Mesa facility was witnessed by an NR materials engineer. The production run witnessed was Narmco batch 282, with United Aircraft/Hamilton Standard filament. Quality control tests were conducted by Narmco to qualify the material to GD Specification FMS2C01A; all of the specification's requirements were exceeded. This batch was scheduled to be supplied to NR and GD; however, because of contractual delays, this batch (282) was used to fill another Narmco order. Subsequently, batch 283 was produced with Texaco filament for NR and GD.

Although a "filament is filament" philosophy had been generally accepted at the initial coordination meeting between USAF, NR, GD, and Narmco (i.e., filament from any qualified producer is acceptable and interchangeable, provided it satisfies filament specification requirements), it seemed wise to observe the processing and quality control testing on batch 283 because of the change in filament supplier. The "filament is filament" philosophy implies that all filament qualified to FMS 2002 will produce boron prepreg tape with properties that will qualify the tape to FMS 2001A.

NR personnel observed the Narmco processing and quality control testing of batch 283 with Texaco filament. The production run had been halted since the longitudinal flexural strength requirements of FMS 2001A had not been met, although all other mechanical and physical requirements conformed to this specification. The maximum thickness requirement (0.0054 inch/ply) of FPS 2001 was also exceeded for these specimens. Table II presents the mechanical property data developed from the initial quality control testing at Narmco.

TABLE II. BATCH 283 - QUALITY CONTROL TEST RESULTS (NARMCO)

Property	Spec No.	RT Reqd (ksi)	RT Actual (ksi)	350° F Reqd (ksi)	350° F Actual (ksi)
Longitudinal Flexure	1	225	195	170	188
	2		205		186
	3		<u>211</u>		<u>187</u>
	Avg.		<u>204</u>		<u>187</u>
Transverse Flexure	1	13.0	15.3	8.0	10.1
	2		13.7		13.8
	3		<u>14.1</u>		<u>12.6</u>
	Avg.		<u>14.4</u>		<u>12.6</u>
Interlaminar Shear	1	13.0	15.4	5.0	9.07
	2		14.7		8.41
	3		<u>14.6</u>		<u>9.09</u>
	Avg.		<u>14.9</u>		<u>8.84</u>

For retesting, it is Narmco's normal quality control policy to increase the number of specimens from 3 to 6. Therefore, two additional panels were fabricated for longitudinal flexural testing after the failure of the first quality control specimens to pass the specification requirements. These new specimens exceeded the 0.0054 inch/ply maximum and also did not meet the flexural strength requirement. Flexural strength data for these two laminates are shown in table III.

TABLE III. BATCH 283 - QUALITY CONTROL RETEST RESULTS (NARMCO)

Panel No.	Spec No.	Flexural Longitudinal Strength (ksi)
A	1	205
	2	195
	3	200
	Avg	200
B	1	201
	2	212
	3	199
	Avg	204

Careful examination of the specimens tested showed that, in addition to their being too thick, they were cut improperly. The long side of the specimen was not cut parallel to the filament but at some small angle to the filaments, resulting in loss of filament continuity from one end of the specimen to the other. Since increased thickness and filament continuity can affect flexural strength, four additional laminates were fabricated with strict attention being paid to filament alignment during layup and cutting, and with provisions for increased resin bleeding to reduce the thickness. The bleed system variation for each of the four laminates is described in table IV.

TABLE IV. BATCH 283 - BLEED SYSTEM FOR SECOND QUALITY CONTROL RETEST

Laminate No.	Layup Description
1	Same as Narmco standard process*, except three plies of 120 glass fabric cut to same size as layup and two small holes placed in mylar film at opposite corners 1/2 inch from each edge
2	Same as standard except four plies of 120 glass fabric cut 1/2 inch larger than layup.
3	Same as laminate 2 except holes in mylar as described in laminate 1.
4	Same as laminate 2 except five plies of 120 glass bleeder. * Essentially identical to NR Process Specification ST0105LA0007, reproduced in this report as Appendix II.

The increase in bleed systems described in table IV did not change the cured laminate thickness to the extent that might be expected. Thicknesses of each of the cured laminates, along with flexural strengths which again did not meet the requirements of FMS 2001A, are shown in table V.

TABLE V. BATCH 283 - SECOND QUALITY CONTROL RETEST RESULTS

Laminate No.	Specimen No.	Thickness* (in.)	Flexural Strength (ksi)	Flexural Modulus (Msi)
1	1	0.083	190	27.1
	2	0.084	195	25.3
	3	0.082	194	24.4
	Avg	0.083	193	25.6
2	1	0.081	204	26.2
	2	0.080	217	27.8
	3	0.080	205	26.3
	Avg	0.080	209	26.8
3	1	0.080	207	26.8
	2	0.079	226	28.9
	3	0.079	219	28.4
	Avg	0.079	217	28.0
4	1	0.080	210	25.7
	2	0.080	207	27.8
	3	0.080	195	27.3
	Avg	0.080	204	26.9
* Allowable thickness (15 plies) = 0.0765 - 0.0810 inch				

Since all of the quality control tests conducted that were matrix-critical passed the requirements of FMS 2001A, and the filament-critical longitudinal flexural quality control test did not pass, filament strengths were examined. Table VI shows the relationship of filament strength to flexural strength for batch 283 and the batches just prior to and following batch 283.

On the basis of these limited data, NR incorporated into its material specification a filament strength requirement of 450 Ksi (min. avg.).

NR accepted 500 feet of batch 283 to be utilized for materials development and familiarization.

TABLE VI. BATCH 283 - FILAMENT STRENGTH VERSUS FLEXURAL STRENGTH

Batch	Filament Manufacturer	Filament Tensile Strength (ksi)	Flexural Strength (ksi)
283	Texaco	423 413 (1)	204 (2)
Prior to 283	Hamilton Standard	459	Exceeded 225
Following 283	Hamilton Standard	445	Exceeded 225
NOTES: (1) Narmco tests - average of 26 spools (2) Average of all flexural data previously presented.			

Four laminates were made from batch 283 per FPS 2001 by three different NR personnel. The thickness was excessive, and the longitudinal flexural strengths were low. As with the Narmco quality control tests on batch 283, the matrix-critical transverse flexure strength requirement was exceeded. These data are shown in table VII.

A meeting was held in Los Angeles between AFML, NR, and GD/FW personnel. GD materials engineers monitored NR fabrication techniques and stated that NR's techniques were in accordance with GD's FPS 2001, and that resultant composites should be of high quality, if the boron prepreg (batch 283) had been acceptable. It was learned that, for quality control laminates, GD used a 104 glass prepreg balance ply. This practice was subsequently adopted at NR. At this time, two laminates were fabricated from batch 282; one by NR and the second by a GD/FW materials engineer. Neither laminate was tested, since both exhibited excessive thickness, i.e., 0.084 inch (NR) and 0.083 inch (GD). A third panel was made using twice as much bleeder (six plies of 120 glass), and its thickness was 0.086 inch.

GD agreed to send NR a small quantity of boron prepreg tape that passed the quality control requirements of FMS-2001A from another program so that NR could determine the efficacy of their fabrication methods. This material from Narmco batch 279 was received, and the NR-fabricated laminates passed all the FMS-2001A requirements. These data are shown in table VIII.

NR fabricated two additional 15-ply laminates from batch 283 using special techniques to increase the resin bleed in an attempt to decrease the laminate thickness. One method used was to provide three plies of 120 glass bleeder on each side of the laminate, and the second was to provide a resin reservoir at each end of the composite to allow resin bleeding parallel to the filaments. Neither method resulted in any significant effect on

TABLE VII. BATCH 283 - PERSONNEL FAMILIARIZATION PANELS TEST RESULTS

Laminate No.	Specimen No.	Thickness (in.)	Longitudinal Flexural Strength (ksi)	Thickness (in.)	Transverse Flexural Strength (ksi)
NR-1	1	0.083	201	0.082	14.5
	2	0.083	185	0.082	13.0
	3	0.084	184	0.083	13.8
NR-2	1	-	-	0.080	14.4
	2	0.083	203	0.082	12.7
	3	0.083	197	0.081	13.4
NR-3	1	-	-	0.082	15.9
	2	0.084	184	0.083	14.0
	3	0.085	194	0.084	14.0
NR-4	1	0.085	186	0.083	13.5

TABLE VIII. BATCH 279 - TEST RESULTS FROM KNOWN GOOD MATERIAL (NARMCO BATCH 279)

Property	Specimen No.	Thickness (in.)	Room Temperature (ksi)	Thickness (in.)	350° F (ksi)
Longitudinal flexural strength	1	0.079	229	0.080	213
	2	0.080	243	0.080	204
	3	0.080	233	-	-
	Avg		235		209
Transverse flexural strength	1	0.080	14.4	0.080	12.7
	2	0.080	14.9	0.080	11.9
	3	0.080	14.9	0.080	12.7
	Avg		14.8		12.4
Horizontal shear strength	1	0.080	16.3	0.078	7.1
	2	0.079	15.9	0.080	7.8
	3	0.080	15.9	0.079	6.9
	Avg		16.0		7.3

thickness over previous specification methods. The thicknesses were 0.083 and 0.084, respectively.

No other attempts were made to utilize any of the remaining material from batch 283.

NARMCO 5505 - BATCH 288 (HAMILTON STANDARD FILAMENT)

The prepregging and subsequent Narmco quality control testing were monitored by an NR materials engineer. All specification requirements were met.

Subsequent NR quality control acceptance tests were conducted. During the cure of the NR laminate, both pressure and temperature were temporarily lost and a resin-rich laminate was produced, resulting in a slight increase in laminate thickness. Increased resin content usually does not affect transverse flexural and horizontal shear strengths to the extent that it affects the longitudinal flexural strength. A second quality control panel was fabricated, and no problems were encountered during the cure. The mechanical property test results of the Narmco tests and both NR panels are shown in table IX.

TABLE IX. BATCH 288 - NARMCO AND NR QUALITY CONTROL TEST RESULTS

Test	Narmco Data		NR Data		NR Remake	
	RT	350°F	RT	350°F	RT	350°F
Longitudinal flexural strength (ksi)	253	207	227	187	233	209
Transverse flexural strength (ksi)	17.0	12.7	15.0	14.6	16.8	14.5
Interlaminar shear strength (ksi)	13.5	5.5	15.7	8.4	16.1	8.7

NARMCO 5505 - BATCH 297 (HAMILTON STANDARD FILAMENT)

Batch 297 was qualified by both Narmco and NR quality control testing. These data are shown in table X.

Further examination of this batch of material revealed that this material had a tendency to roll up across its 3-inch width. It was further determined that this rolling or curling problem was more severe with the last roll received by NR/LAD (No. 52) than it was with the first roll (No. 1).

This curling effect is shown in figures 3 and 4. The lengths of prepreg tapes shown in these figures are 1, 2, 3, 4, and 5 feet, respectively. It appeared that lengths of up to 2 feet could be handled without difficulty, 3-foot lengths would be marginal in handling, and lengths beyond 3 feet would be very difficult to handle from a fabrication standpoint.

TABLE X. BATCH 297 - NARMCO AND NR QUALITY CONTROL TEST RESULTS

Test	Narmco Data		NR Data	
	RT	350°F	RT	350°F
Longitudinal flexural strength (ksi)	247	230	251	213
Transverse flexural strength (ksi)	16.6	10.1	16.5	12.7
Interlaminar shear strength (ksi)	15.3	5.5	15.8	7.9

Narmco studies revealed that the boron filament was twisted (from one turn in 2 feet to one turn in 13 feet) and suggested that this could be the cause of the tape curling characteristics. Since it was observed that the curling problem was more severe for roll 52 than roll 1, roll 52 was tested for mechanical properties to determine if the degree of tape curl affected these properties. These data are shown in table XI, and significant difference in longitudinal flexural strength can readily be seen.

Since further exploration of the effect on mechanical properties of twisted tape was deemed desirable, a small testing program was initiated. It was agreed between NR and GD, who also was cognizant of the tape curling problem, that IITRI* type unidirectional tensile specimens (figure 11) would be exchanged. Both NR and GD fabricated 10 [0]_{6T} coupons from rolls 51 (GD) and 52 (NR) with five specimens tested by the fabricator and the other five interchanged and tested. These data are shown in table XII.

These data are below the 186 ksi average tensile strength of batch 288 (acceptable material in all respects) obtained by IITRI. This correlates well with low longitudinal flexural strength obtained on rolls 51 and 52.

These test data also indicate that NR and GD test techniques are equivalent. The data are based on a nominal ply thickness of 0.0052 inch.

All of the available longitudinal flexural data are shown in table XIII.

* Illinois Institute of Technology Research Institute

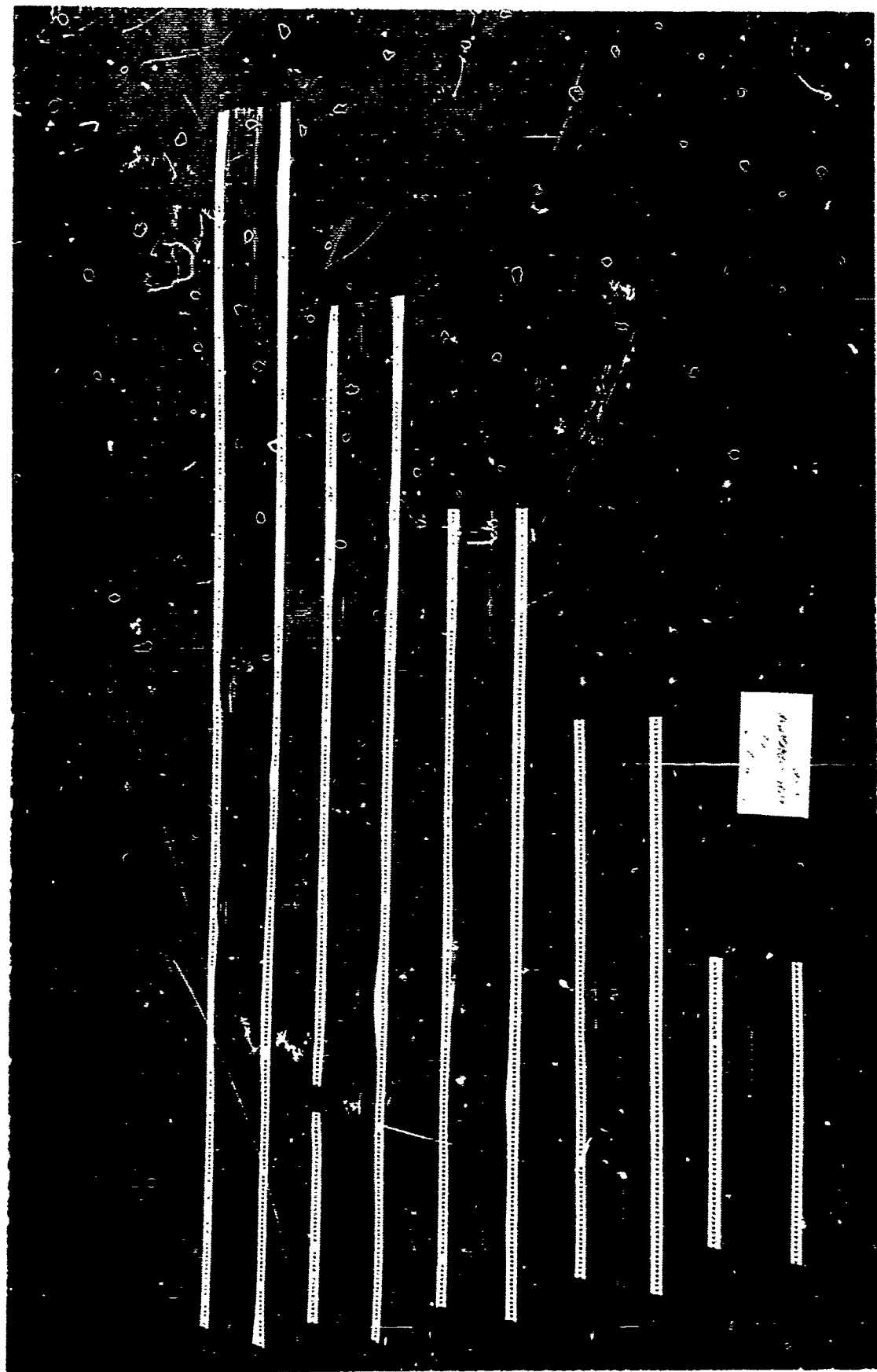


Figure 3. Batch 297 Samples with Separator Paper

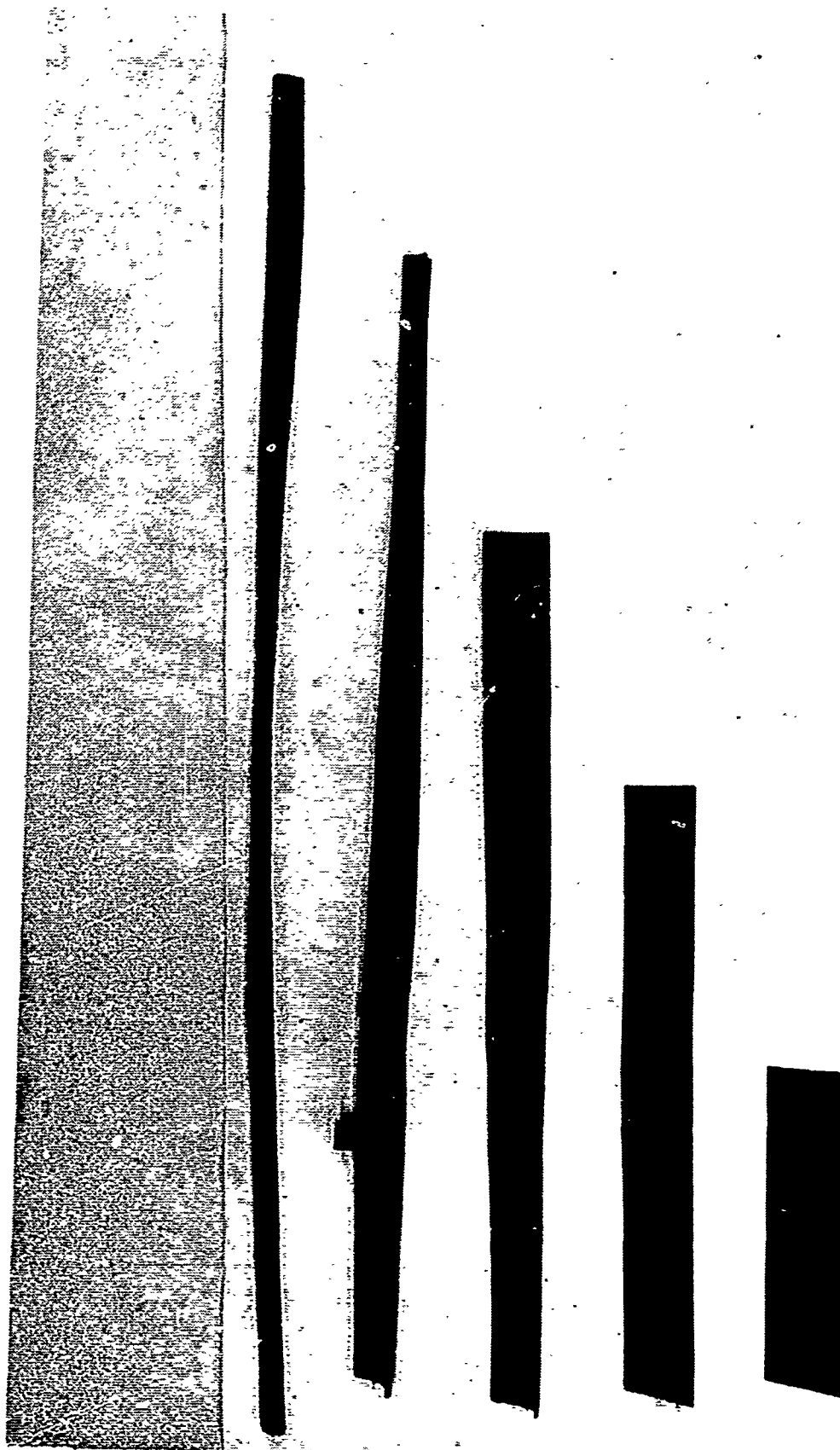


Figure 4. Batch 297 Samples Without Separator Paper

TABLE XI. BATCH 297 - QUALITY CONTROL TEST RESULTS VERSUS SEVERITY OF TWIST

Test	Roll 52 Data		Roll 1 Data	
	RT	350°F	RT	350°F
Longitudinal flexural strength (ksi)	231 (1)	196	251	213
Transverse flexural strength (ksi)	13.0 (2)	12.3	16.5	12.7
Interlaminar shear strength (ksi)	14.8	7.9	15.8	7.9
NOTES: (1) One test value (223.9 ksi) out of three did not meet the requirement of 225 ksi per appendix I. (2) One test value (12.1 ksi) out of three did not meet the requirement of 13 ksi per appendix I.				

TABLE XII. BATCH 297 - TEST RESULTS OF INTERCHANGE BETWEEN NR AND GD TWISTED TAPE

Tested by	NR Fabricated (Roll 52)	GD Fabricated (Roll 51)
NR	153 ksi 166 157 160 187 <hr/> 165 avg	173 ksi 175 178 174 192 <hr/> 178 avg
GD	181 175 178 161* 139* <hr/> 178 avg	171 172 175 172 189 <hr/> 176 avg

* Specimens were improperly gripped and have been discounted.

TABLE XIII. BATCH 297 - SUMMARY OF AVAILABLE DATA BY ROLL

Roll No.	Longitudinal Flexural Strength (ksi)	Data Source
1	251	NR
1	247	Narmco
6	285	Narmco
30	265	Narmco
43	219 (1)	GD
50	219 (1)	GD
52	231 (2)	NR
NOTES: (1) The 350°F strengths were below the appendix I requirement of 170 ksi. The averages at 350°F were 154 ksi for roll 43 and 156 ksi for roll 50. (2) One value out of three was 223.9 ksi, which is below the 225 ksi requirement of appendix I.		

As previously mentioned, there was some evidence that the curling problem was more severe in the latter rolls than the initial rolls. Table XIII reflects what may be a degrading effect on the latter rolls of prepreg tape due to curling.

Mechanical property test data from NR and GD, along with limited data from both Narmco and Grumman, are shown in table XIV. These data are also shown in graphic form in figure 5 along with Narmco resin content measurements and the thickness measurements available from table XIV. The physical property measurements conducted at NR are presented in table XV.

All these data were accumulated and presented by GD and NR at a meeting at Narmco, Costa Mesa, California, at which most of the major aerospace users were in attendance.

A careful review of the data presented in table XIV shows that all the rolls in runs 1 and 2 meet the acceptance standards contained in appendix I. It was agreed that all these rolls would be used in the NR structural element program. The below-specification (FMS 2001A) performance of rolls 14 through 52 was cause for rejection, and rolls 19, 20, 21, 24, 29, 37, 38, 39, 44, 45, 46, 47, 49, and 52 were returned to Narmco.

This meeting was primarily stimulated by the severe twist or curl evident in batch 279 and other currently produced boron/epoxy prepreg tapes. Narmco had received approximately 1 pound each of filament from (1) UAC that had what was judged to be twist of a magnitude comparable to that used in current batches of prepreg tapes, (2) UAC that had low twist, and (3) AVCO that had no

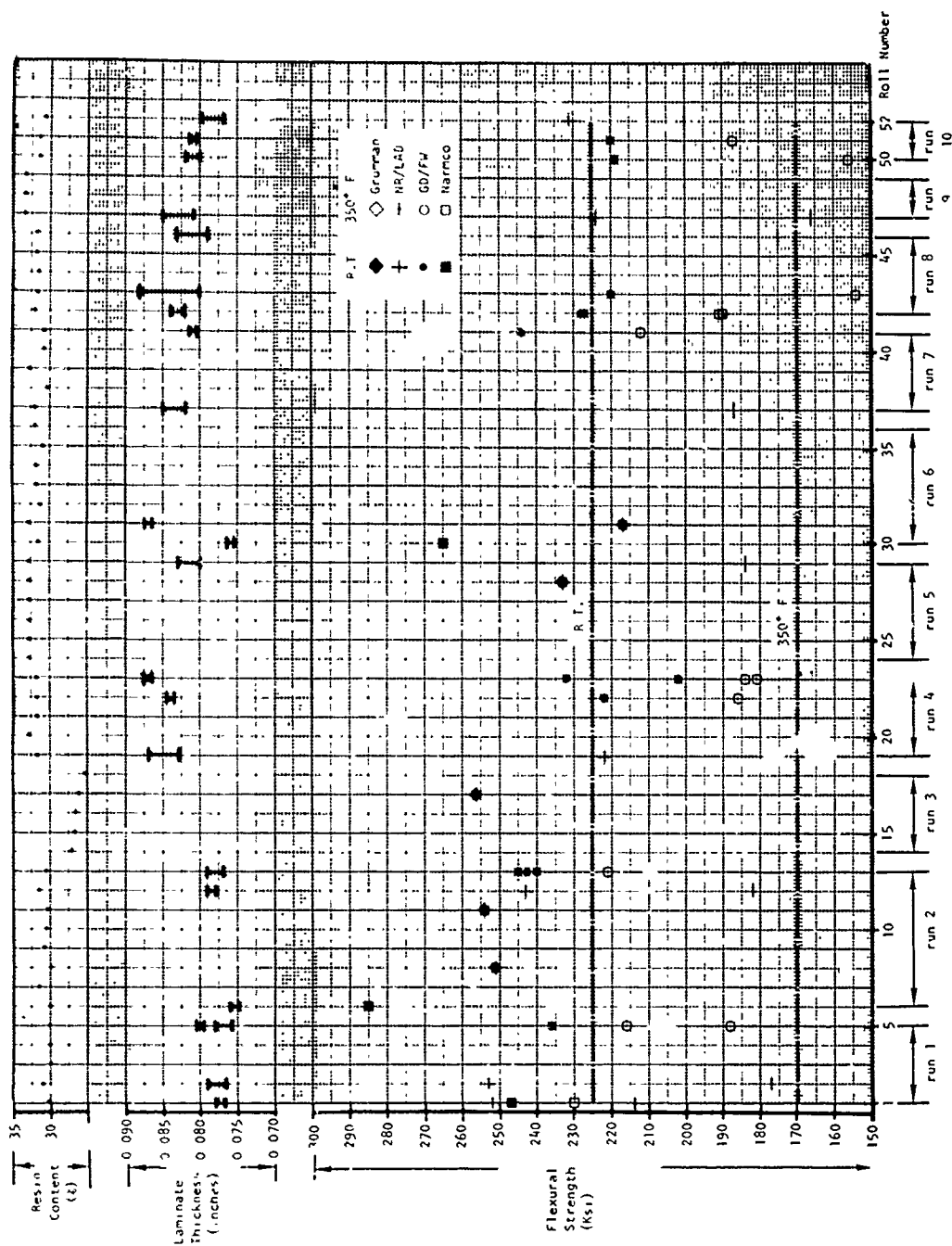


Figure 5. Batch No. 297 Quality Control Data

TABLE XIV. BATCH 297 ACCEPTANCE DATA

Roll	Source	Thickness	0° Flex ksi				90° Flex ksi				Shear ksi			
			RT	270	350	420	RT	270	350	420	RT	270	350	420
1	Narmco	0.078-0.078	247		230		16.6				15.3		5.5	
2	Narmco	0.077-0.079	252		214		16.5				15.8		8.0	
5	NR	0.076-0.078	253		177		16.2				15.0		7.4	
	GD	0.076-0.078	253	226	188	94	16.2	14.7	10.1	5.7	16.6	8.8	6.6	3.6
6	GD	0.080	236		216		16.4				15.5			
8	Narmco		285											
	Grumman		251		(185)									
11	Grumman		254		(168)									
12 (30.3%)	NR	0.078-0.079	243		182		15.8		9.0		15.0		7.1	
13	GD	0.077	245				15.2				16.0			
	GD	0.079	240		221		16.1		12.5		15.3			
	GD	0.079	241				15.1				15.0			
17	Grumman		256											
19 (34.6%)	NR	0.083-0.087	222		170		14.7		11.1		15.5		7.5	
22	GD	0.084	222		186		15.8		12.4		15.4		8.4	
23	GD		232		184		15.5		10.6		16.4		7.3	
	GD	0.087	202		181		15.0		9.2		13.5			
28	Grumman		233		(175)									
29 (32.9%)	NR	0.080-0.08	240		184		16.0		10.0		15.4		7.4	
30	Narmco	0.076	265											
31	Grumman	0.087	217		(157)									
37 (33.9%)	NR	0.082-0.085	240		187		15.0		9.1		15.0		74	
41	GD	0.081	244		212		15.5		11.3		16.0			
42	GD	0.084	227		190		15.0		11.3		14.5			
	GD	0.082	228		191		15.0		11.9		15.4			
43	GD	0.082-0.088	220		154		15.2		10.3		15.9		5.8	
	GD	0.080	225		196		12.8		9.9		14.9			
46 (32.8%)	NR	0.079-0.083	240		175		15.0		9.0		15.0		7.4	
47 (34.7%)	NR	0.081-0.085	224		166		15.0		11.0		15.0		7.6	
50	GD	0.080-0.083	219		156		15.2		11.4		16.0		5.7	
51	GD	0.081	220		187		15.2		12.8		15.9			
52	NR	0.077-0.080	231		200		13.0		12.0		15.0		8.0	

TABLE XV. PHYSICAL PROPERTIES OF BATCH 297

Roll No.	Tack	Resin Flow (%)	Volatile Content (%)	Resin Content (%)
2	Acceptable	11.5	0.4	31.4
12	Acceptable	10.8	0.5	30.3
19	Acceptable	16.1	0.6	34.6 (1)
29	Acceptable	13.7	0.5	32.9
37	Acceptable	13.3	0.5	33.9
46	Acceptable	10.4	0.5	32.8
47	Acceptable	14.4	0.5	34.7 (1)
NOTE: (1) Does not meet the specification requirements of 29-34%.				

twist. Both 1/8-inch and 3-inch prepreg tapes from each type of filament are shown in figure 6. The high-twist UAC filament produced both 1/8-inch and 3-inch tapes with high twist. The low-twist UAC filament produced tapes with only a trace of a tendency to twist, and the AVCO nontwisted filament produced tapes with no twist. From this direct evidence, it was concluded that filaments which are twisted produce boron/epoxy prepreg tapes that also twist, and untwisted filament produces flat tape with no tendency to twist or curl.

A further manifestation of the tape-twisting problem occurred during attempts to use batch 297 to fabricate panels for the structural element program. (This program is covered in volume II of this report.) Curling was so severe that attempts to use this batch were abandoned. Figures 7 and 8 illustrate the impracticality even of laying up satisfactory panels with these tapes.

Since many of the quality control specimens were out of tolerance with respect to thickness, it was suspected that the resin matrix might be too far advanced. An examination of the physical property data in table XV shows that even though both flow and resin content were within the specification (appendix I), the resultant composites in some cases (e.g., rolls 29 and 37) were too thick. It would appear that flow, as measured in the quality control tests, is possibly not a satisfactory indication of resin advancement, which is a key factor in the ability of the resin to produce proper thickness composites. Narmco used gel time to measure resin advancement, and their specification required 4 ± 0.5 minutes at 300°F, as measured on a Fisher-Johns apparatus. The resin used in prepreg tape batch 297 had a gel time of 4.0 minutes. It was suggested to Narmco that the gel time of this same resin batch which was then on the boron tape should be measured. Three subsequent measurements of gel time of the resin on roll 23 resulted in reduced times of 3 minutes, 30 seconds; 3 minutes, 40 seconds; and 3 minutes, 36 seconds. It



Figure 6. Narmco Tape With Filaments of Various Degrees of Twist (Sheet 1 of 3)

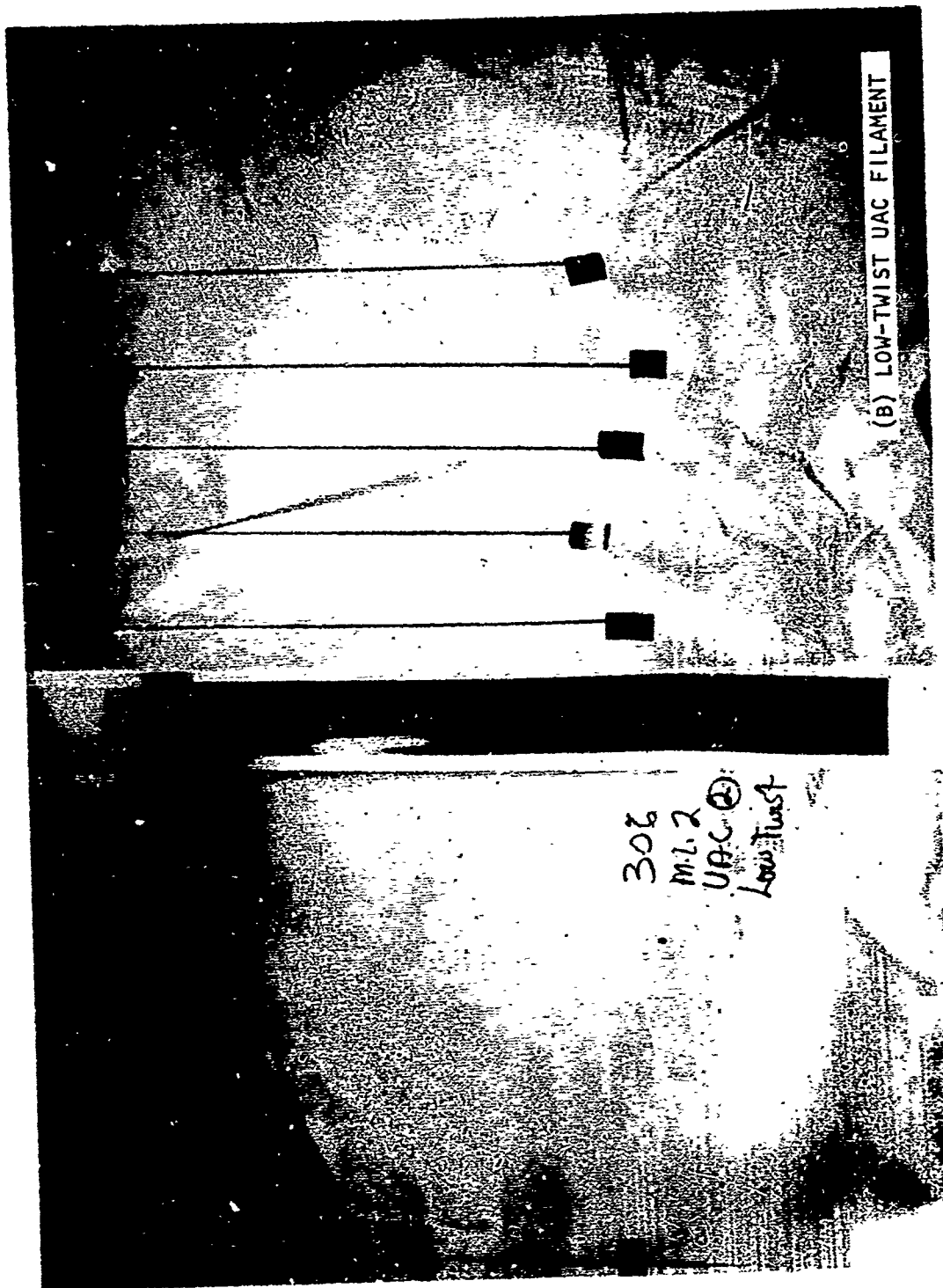


Figure 6. Narmco Tape with Filaments of Various Degrees of Twist (Sheet 2 of 3)

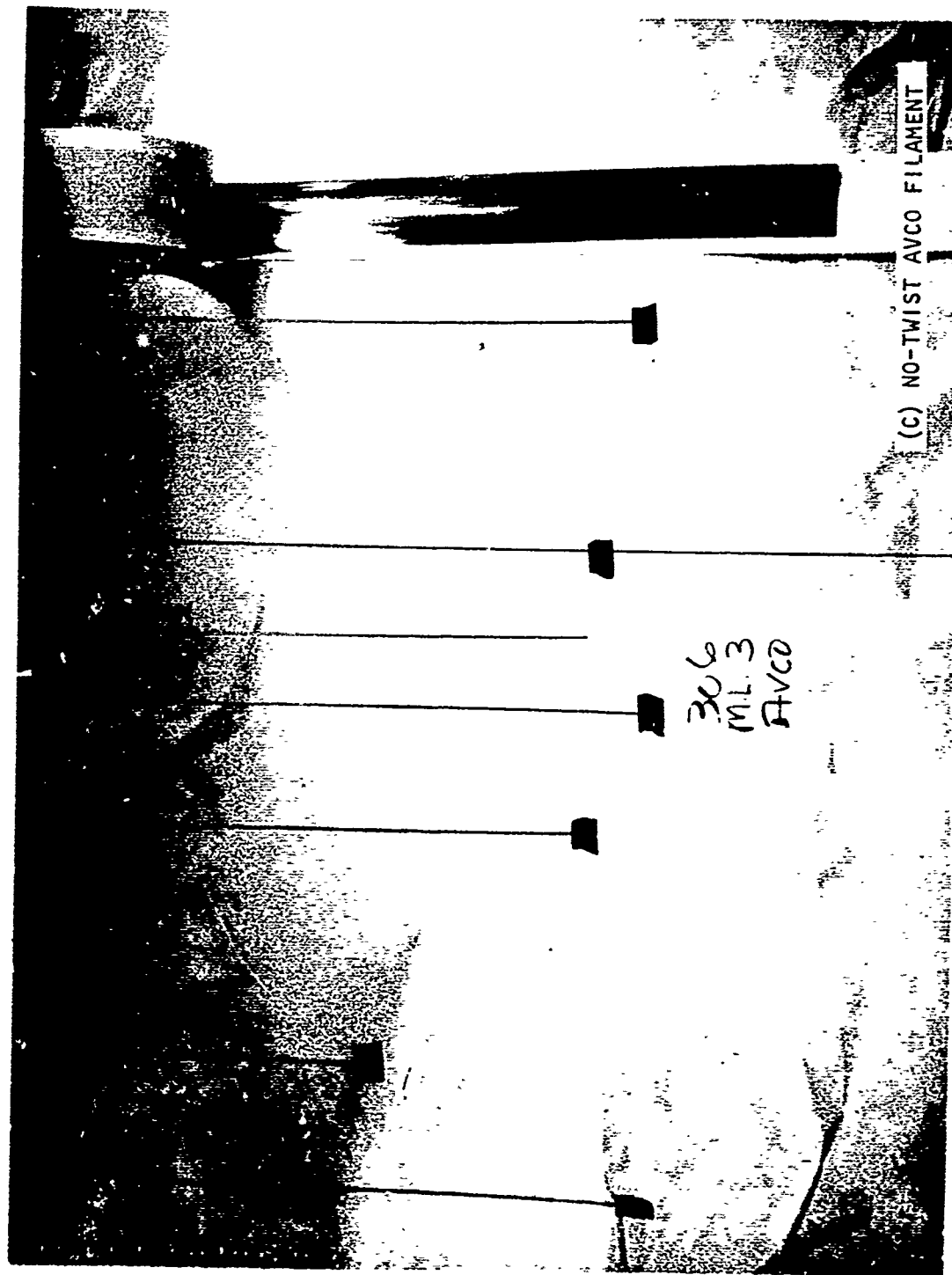


Figure 6. Narmco Tape With Filaments of Various Degrees of Twist (Sheet 3 of 3)

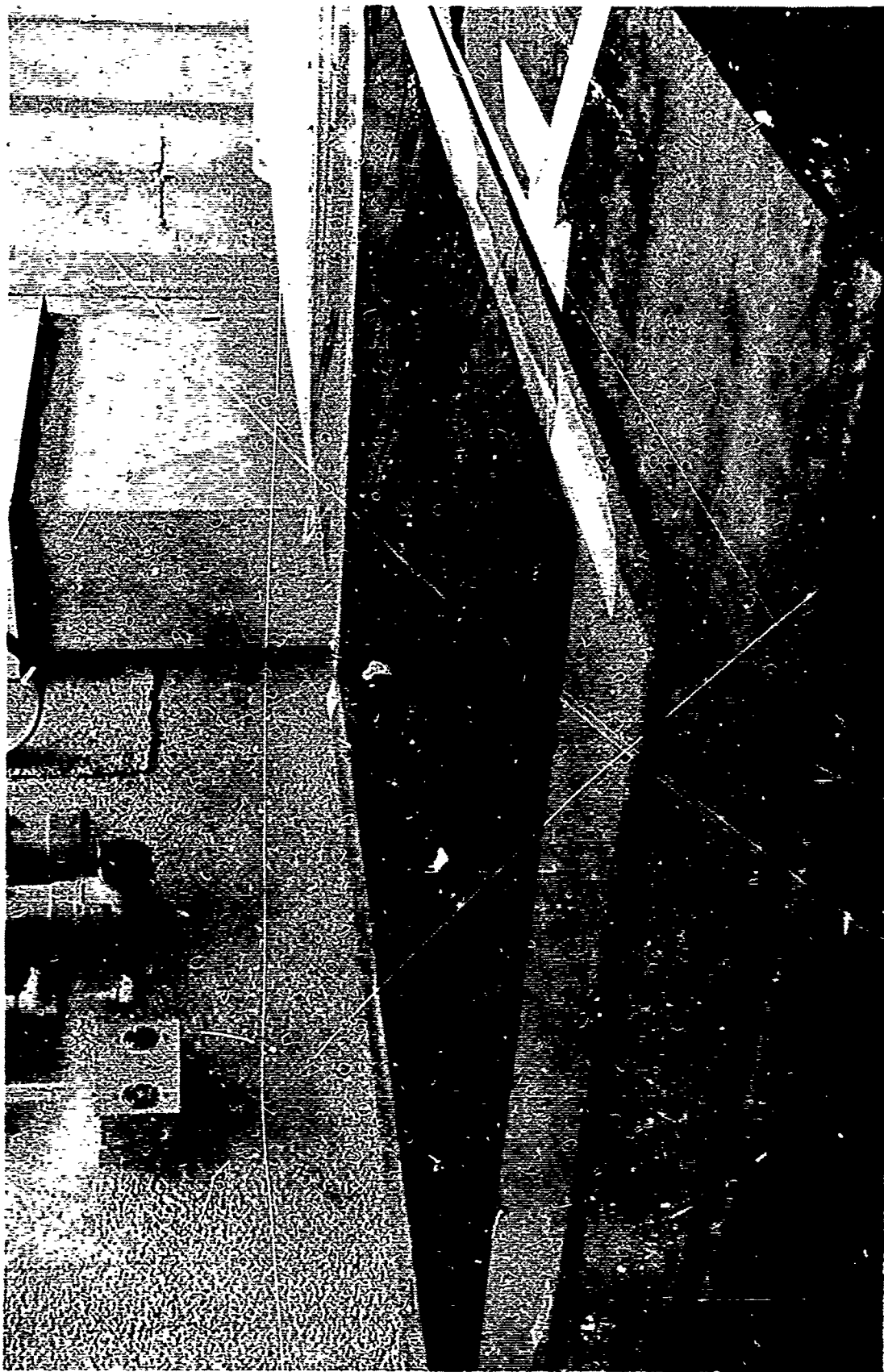


Figure 7. Panel Layout Showing Twisted Tape



Fig. 1. Layup Showing Twisted Tape (1 sec-Up)

was suggested that possibly 4 ± 0.5 minutes gel time might be too short, and the lower gel times may be the problem area relative to composite thickness.

Roll 23 was selected for the gel time measurements because GD had fabricated three quality control 15-ply unidirectional specimens without successfully producing a composite within the required thickness range (0.0775 to 0.082, including 0.001-inch, 104 glass prepreg balance ply). In addition to the gel time measurements on roll 23, quality control composites were made by NR and Narmco using the identical process used by GD to determine if the heat-heatup rate showed any significant difference in finished composite thickness. All the composites fabricated by GD, Narmco, and NR were too thick. These data are shown in table XVI.

TABLE XVI. BATCH 297 - EFFECT OF HEATUP TIME ON LAMINATE THICKNESS

Fabricator	Heatup Time	Thickness Range	Bleeder Fabric Remarks
Narmco - laminate No. 1	40-45 min	0.087-0.088	Complete bleeder saturation
Narmco - laminate No. 2	40-45 min	0.089-0.091	Complete bleeder saturation
GD/FW - three laminates	7 min	0.083-0.087	Incomplete bleeder saturation
NR - laminate No. 1	23 min	0.087-0.089	Incomplete bleeder saturation
NR - laminate No. 2	23 min	0.085-0.091	Incomplete bleeder saturation

The incomplete bleeder fabric saturation shown in figure 9 is a still further indication of resin advancement.

In the final evaluation of batch 297, considering its unpredictable curling characteristics and the wide inconsistency in its properties, it was jointly decided to reject the batch in its entirety.

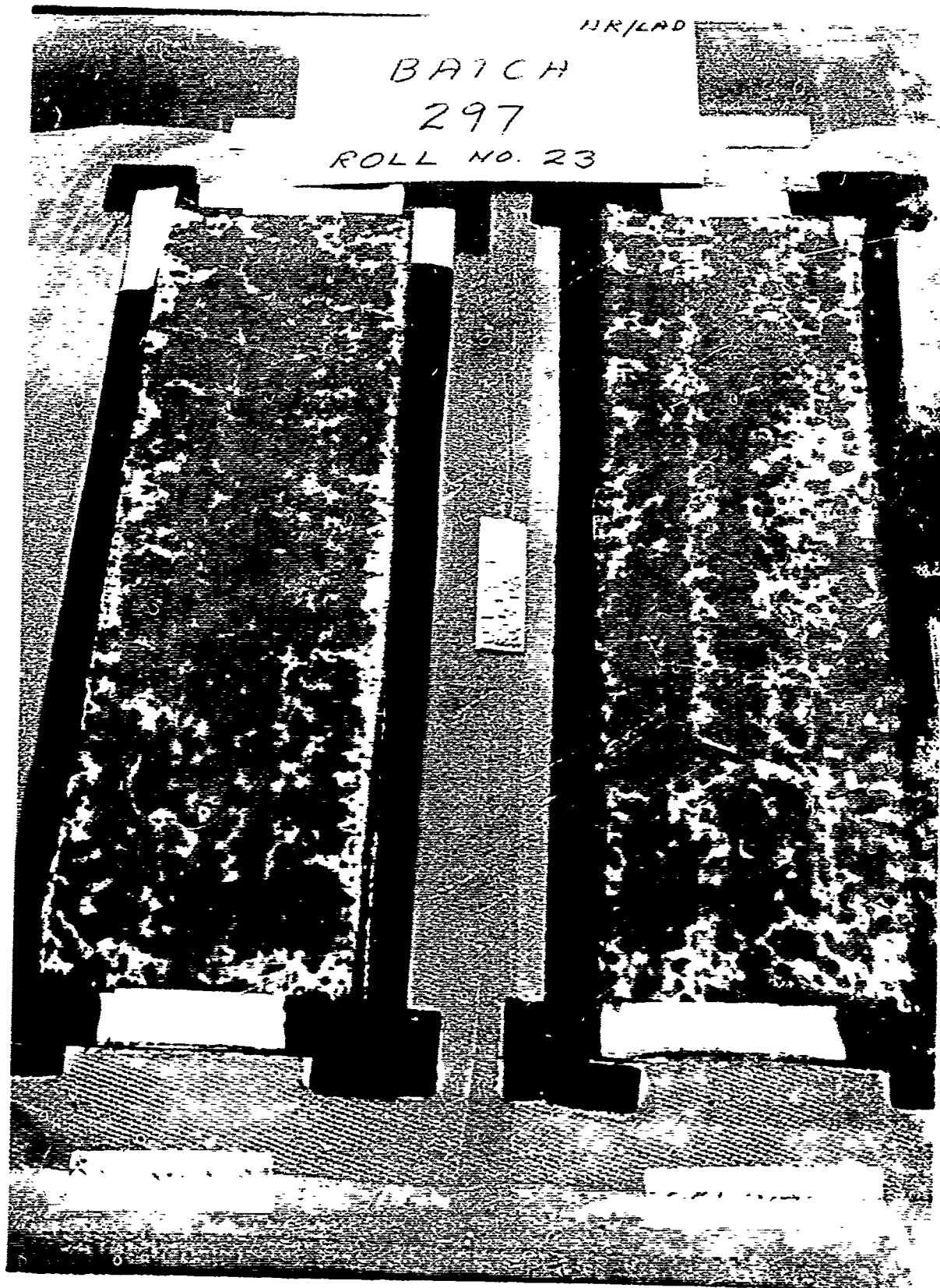


Figure 9. Batch 297 Incomplete Bleeder Fabric Saturation

NARMCO 5505 - BATCH 312 (HAMILTON STANDARD FILAMENT)

Batch 312 qualified in every respect, and the mechanical property acceptance test data are presented in table XVII.

TABLE XVII. BATCH 312 - QUALITY CONTROL TEST RESULTS

Roll No.	Longitudinal Flexure (ksi)		Transverse Flexure (ksi)		Interlaminar Shear (ksi)	
	RT	350°F	RT	350°F	RT	350°F
(*)	259	199	14.1	11.7	15.5	6.0
4	248	241	13.7	12.3	14.8	8.6
5	251	227	13.1	12.1	14.7	8.3
15	247	222	15.3	10.9	14.5	7.2
24	244	206	15.8	11.2	14.6	7.2
(*) Narmco data						

NARMCO 5505 - BATCH 328 (HAMILTON STANDARD FILAMENT)

Batch 328 qualified in every respect, and the mechanical property acceptance test data are presented in table XVIII.

TABLE XVIII. BATCH 328 - QUALITY CONTROL TEST RESULTS

Roll No.	Longitudinal Flexure (ksi)		Transverse Flexure (ksi)		Interlaminar Shear (ksi)	
	RT	350°F	RT	350°F	RT	350°F
1	259	229	13.7	12.4	14.6	8.9
5	259	222	14.5	12.3	14.6	8.9
10	244	210	14.2	11.7	15.5	8.2
15	250	217	14.8	11.8	15.5	8.0
20	235	212	14.3	12.1	15.1	8.4
25	233	212	13.9	11.7	15.2	8.4

NARMCO 5505 - BATCH 334 (HAMILTON STANDARD FILAMENT)

Batch 334 qualified in every respect, and the mechanical property acceptance test data are presented in table XIX.

TABLE XIX. BATCH 334 - QUALITY CONTROL TEST RESULTS

Roll No.	Longitudinal Flexure (ksi)		Transverse Flexure (ksi)		Interlaminar Shear (ksi)	
	RT	350°F	RT	350°F	RT	350°F
1	252	202	15.2	10.3	15.1	6.5
10	241	202	14.0	11.2	15.1	6.6
14	241	197	14.8	11.2	14.9	6.6

NARMCO 5505 - BATCH 348 (HAMILTON STANDARD FILAMENT)

Batch 348 qualified in every respect, and the mechanical property acceptance test data are presented in table XX.

TABLE XX. BATCH 348 - QUALITY CONTROL TEST RESULTS

Roll No.	Longitudinal Flexure (ksi)		Transverse Flexure (ksi)		Interlaminar Shear (ksi)	
	RT	350°F	RT	350°F	RT	350°F
1	236	202	13.2	12.0	14.8	9.3
5	242	214	15.7	11.9	14.6	10.2

NARMCO 5505 - BATCH 364 (HAMILTON STANDARD FILAMENT)

Batch 364 qualified in every respect, and the mechanical property acceptance test data are presented in table XXI.

TABLE XXI. BATCH 364 - QUALITY CONTROL TEST RESULTS

Roll No.	Longitudinal Flexure (ksi)		Transverse Flexure (ksi)		Interlaminar Shear (ksi)	
	RT	350°F	RT	350°F	RT	350°F
364	232	209	13.5	11.8	15.1	9.5

CONCLUSIONS

With the exception of Narmco batches 283 and 297, all boron/epoxy prepreg tape received was acceptable and of reasonably consistent high quality. The average mechanical property test results for all the acceptable tape batches are summarized in table XXII.

TABLE XXII. SUMMARY OF QUALITY CONTROL DATA

Batch No.	Longitudinal Flexure (ksi)		Transverse Flexure (ksi)		Interlaminar Shear (ksi)	
	RT	350°F	RT	350°F	RT	350°F
288	233	209	16.8	14.5	16.1	8.7
312	248	224	13.5	11.4	14.7	7.8
328	247	217	14.2	12.0	15.1	8.5
334	245	201	14.7	10.9	15.0	6.6
348	239	207	13.5	12.0	14.7	9.8
364	232	209	13.5	11.8	15.1	9.5
Spec reqmt	225	170	13.0	8.0	13.0	5.0

On the basis of the filament strength and composite strength data from batch 283, NR wrote into its materials specification a requirement for 450 ksi as the minimum average filament strength that would be acceptable for use in prepreg tape.

VERIFICATION TEST PROGRAM

A verification test program was undertaken at the beginning of the contract to insure that composite laminate fabrication procedures and testing techniques would provide high-quality specimens and valid data. This program covered a series of tests on two basic orientations, $[0]_C$ and $[0_2/\pm 45]_C$, on which a relatively large quantity of data was available for comparison.

A summary of the verification program indicating specimen type, quantity, and instrumentation is given in figure 10. Sketches of the specimens are shown in figure 11.

Interlaminar shear and flexure testing of thin laminates posed special problems because of the small magnitude of the failing loads and the loading conditions required to make critical the interlaminar shear mode of failure. Previously, such tests have utilized especially thick laminates. However, the need for a capability of testing the widely used thin laminates directly, as represented by these three- to eight-ply specimens, was highly desirable. Thus, a new interlaminar shear loading configuration and specific modifications of conventional flexural test procedures were developed for quality control tests for thin laminates. The possible loading arrangements, resulting moment and shear values, and the shear-to-moment ratio are shown in configurations A through G of figure 12. Use of the conventional interlaminar shear specimen, type B of figure 12, did not provide critical interlaminar shear in any of the laminates to be tested. However, when the loading was moved offcenter to the quarter-span point, the shear load increased while the bending moment decreased, as shown in specimen type A. This resulted in critical interlaminar shear in the six- and eight-ply specimens and near-critical shear in the three- and four-ply specimens. On the basis of this result, special adapter fittings, shown in figure 13, were made for use with the basic test fixture to provide a 0.10 inch offset of the load. Longitudinal flexural tests were conducted with the conventional 2.0-inch span, quarter-point loading configuration (type D of figure 12).

Very low failing loads were predicted for transverse flexure because of the thin laminates and low transverse strengths. Using the same 2.0-inch span, quarter-point loading configuration, predicted failing loads are from 0.53 to 5.7 pounds. For low loads, the 0.40-inch span, centrally loaded (type B) specimen increases the failing load by a factor of 2.50. The 0.40-inch span was therefore used for the three- and four-ply laminates, and the 2.0-inch span, quarter-point loading for the six- and eight-ply laminates.

An additional problem resulting from the very low failing loads was the need to counterbalance the approximately 4-pound movable loading head of the test fixture. This was accomplished by adding a spring between the fixture frame and plunger guide arm and calibrating the system as a function of head position.

LONGITUDINAL TENSILE TEST RESULTS

The unidirectional $[0]_3T$ and $[0]_6T$ longitudinal tensile specimen failing stresses from the initial tests were considered to be unsatisfactory because of excessive scatter in the results. Consequently, the test technique was modified and new specimens machined for retest. This change consisted of

QUALITY VERIFICATION OF NR/LAD B/EPOXY (5505) FABRICATION AND TEST PROCEDURES

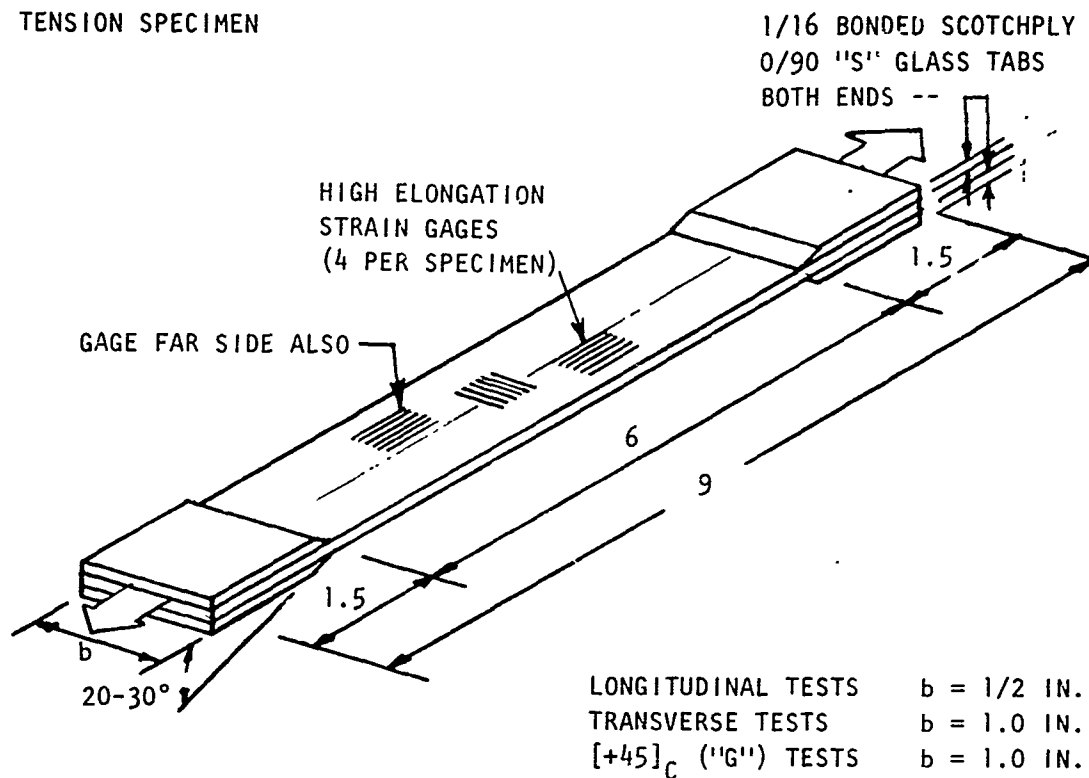
TYPE TEST		LAMINATE ORIENTATION	THICKNESS (PLIES)	SPECIMEN TYPE AND SIZE	NO. OF SPECIMENS	INSTRUMENTATION & STRAIN GAGE REQUIREMENTS
TENSION	LONG.	[0] _c	3-PLY	IITRI 1/2 X 9 IN.	4	1 SPEC: STRAIN GAGED: 0, 90 DEG 3 SPEC: EXTENSOMETER
			6-PLY		4	
		[0/±45/0] _{nT}	4-PLY		4	
			8-PLY		4	
	TRANS	[0] _c	3-PLY	IITRI 1 X 9 IN.	4	1 SPEC: STRAIN GAGED: 0, 90 DEG 3 SPEC: EXTENSOMETER
			6-PLY		4	
		[0/±45/0] _{nT}	4-PLY		4	
			8-PLY		4	
COMPRESSION (LONG).		[0]	3-PLY	BEAM** GD/FW 1 IN. X 22 IN.	2	STRAIN GAGE ALL SPECIMENS WITH 0 & 90 DEG GAGES
			6-PLY		2	
		[0/±45/0] _{nT}	4-PLY	23 LB/CU FT H/C CORE	2	
			8-PLY		2	
IN-PLANE SHEAR MODULUS (BY CALC FROM TENSILE SPECIMENS)		[+45] _c *	3-PLY	IITRI 1 X 9 IN.	3	ALL SPECIMENS: GAGE IN LINE WITH LOAD
			6-PLY		3	
INTERLAMINAR SHEAR (LONG.)		[0] _c	3-PLY	GD/FW 0.25 X 0.6 IN.	4	NO INSTRUMENTATION
			6-PLY		4	
		[0/±45/0] _{nT}	4-PLY		4	
			8-PLY		4	
FLEXURE	LONG.	[0] _c	3-PLY	GD/FW 1/2 X 4 IN.	3	NO INSTRUMENTATION
			6-PLY		3	
		[0/±45/0] _{nT}	4-PLY		3	
			8-PLY		3	
	TRANS	[0] _c	3-PLY	GD/FW 1/2 X 3 IN.	3	NO INSTRUMENTATION
			6-PLY		3	
		[0/±45/0] _{nT}	4-PLY		3	
			8-PLY		3	
TOTAL					86	

* MADE FROM $[0]_c$ PANEL

** BONDED USING TWO LAYERS AF130 ADHESIVE PER FACE. CURED AT 45 PSI FOR 1 HOUR AT 350° F.

Figure 10. Quality Verification Test Program for Boron/Epoxy Laminates

TENSION SPECIMEN



COMPRESSION SPECIMEN

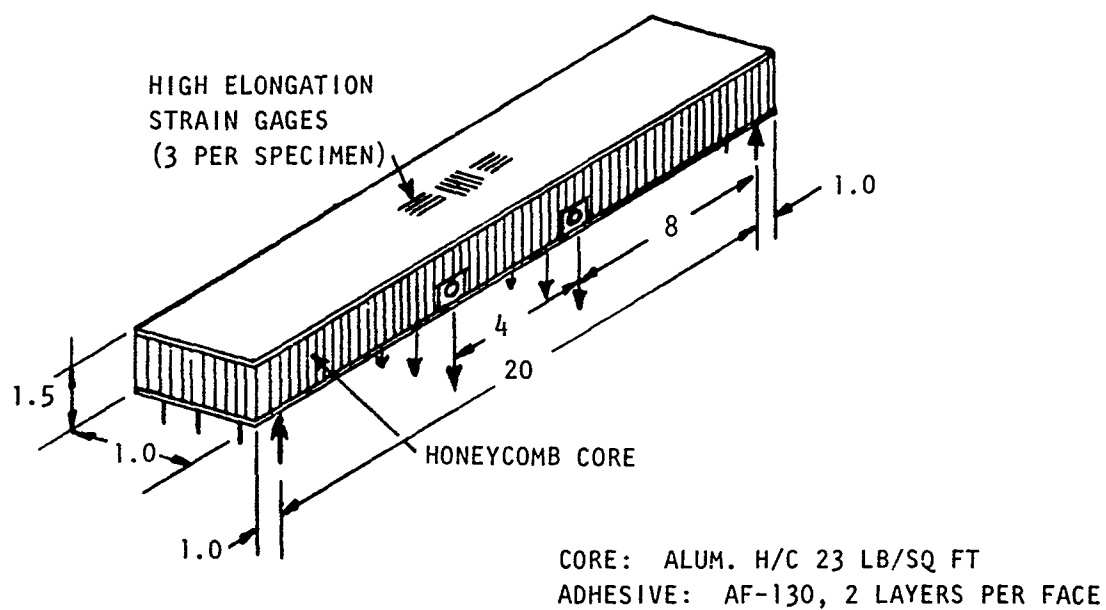


Figure 11. Tensile and Compressive Verification Test Specimens

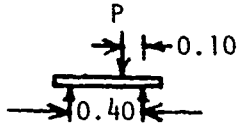
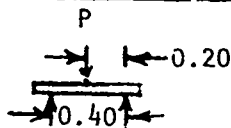
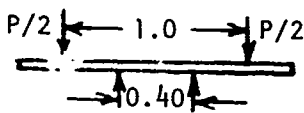
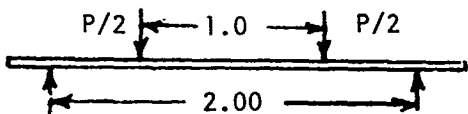
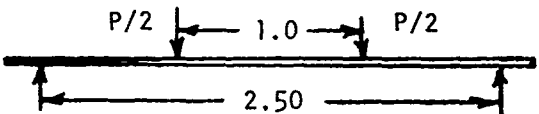
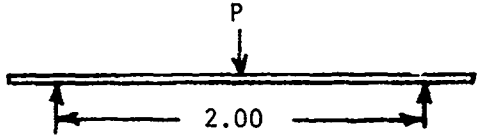
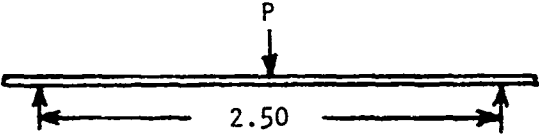
PRINCIPAL APPLICATION	SPECIMEN AND LOADING	MAX MOMENT IN.-LB	MAX SHEAR LBS	RATIO SHEAR/MOM (1/IN.)
A. SPECIAL INTERLAM. SHEAR		0.075P	0.75P	10.00
B. INTERLAM. SHEAR		0.10P	0.50P	5.00
C. SPECIAL FLEXURE		0.15P	0.50P	3.33
D. TRANS. FLEXURE		0.25P	0.50P	2.00
E. SPECIAL FLEXURE		0.375P	0.50P	1.33
F. LONG. FLEXURE (0.060 -0.070)		0.50P	0.50P	1.00
G. LONG. FLEXURE (0.081 -0.090)		0.625P	0.50P	0.80

Figure 12. Summary of Flexural Test Fixture Loading Configurations

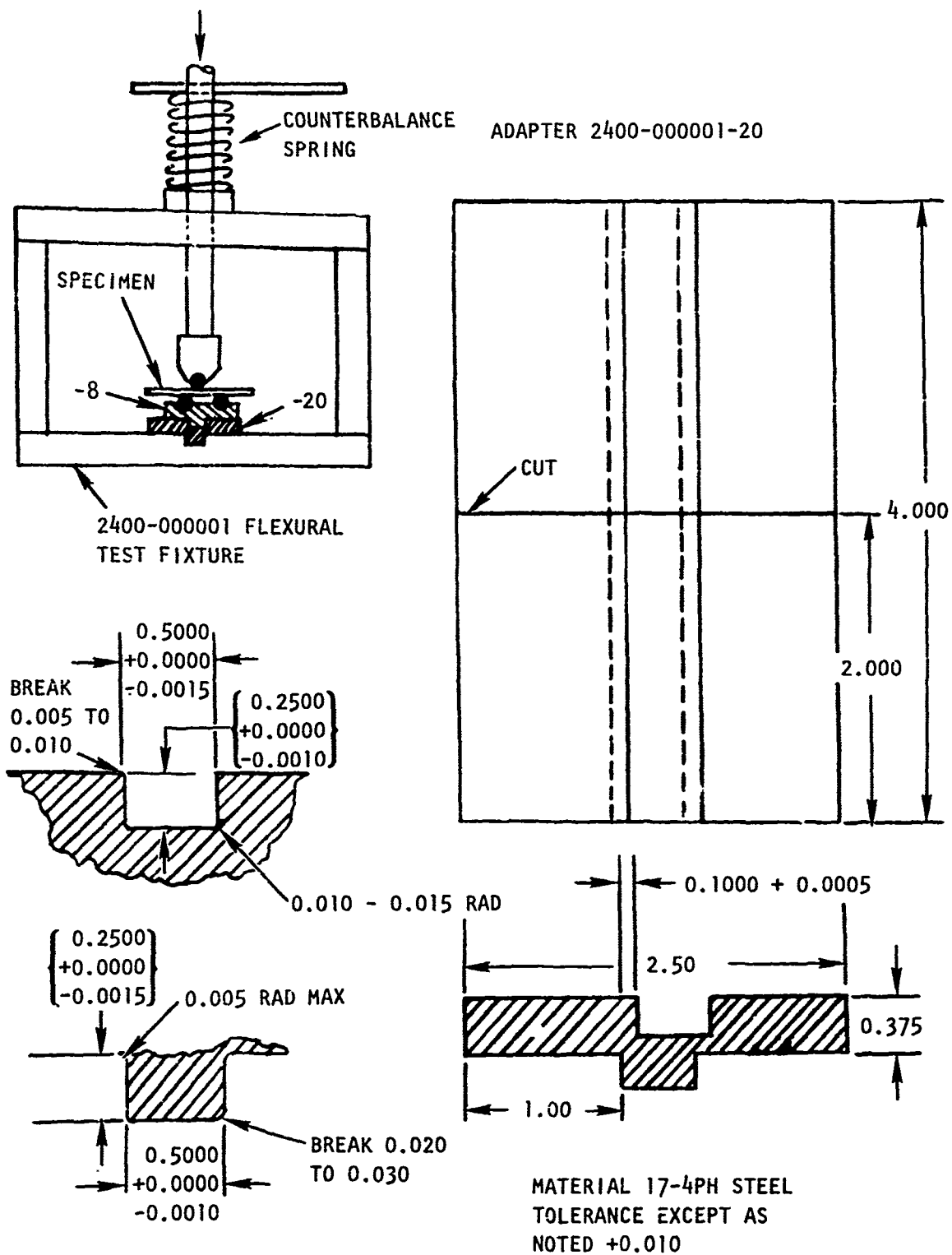


Figure 13. Test Fixture Adapter for Offset Interlaminar Shear Test

eliminating the tensile rods between the grips and the machine head and attaching the grips rigidly to the machine heads.

Original results varied from 158 to 184 ksi for the $[0]_3T$ specimens and 159 to 177 ksi for the $[0]_6T$ specimens. Comparable values for retested specimens are shown in the following tabulation:

$[0]_3T$ Longitudinal Failing Stress (ksi)

<u>Original Test</u>	<u>Retest</u>
184	184
176	180
162	177
158	153
Average 170	Average 174

$[0]_6T$ Longitudinal Failing Stress (ksi)

<u>Original Test</u>	<u>Retest</u>
177	192
174	189
168	187
158	184
Average 169	Average 188

The new technique provided a definite improvement in the strength level and consistency of the six-ply specimens. This improvement resulted from the elimination of secondary bending stresses due to better alignment and centering of the load. However, little improvement in either scatter or average stress was accomplished in the three-ply specimens. This may be characteristic of the thinner laminate.

Comparison of the $[0/\pm 45/0]_{nT}$ four- and eight-ply laminate longitudinal results indicates extremely good consistency in failing stress (97.6 versus 98.6 average values) and longitudinal deformation. A significant difference in transverse strain ϵ_y is noted; the four-ply material was found to have a lower ϵ_y than the eight-ply because of a surface ply effect which is discussed more fully under the transverse tensile test results.

Longitudinal tensile specimen data are summarized in tables XXIII through XXVI and plotted in figures 14 through 19.

TABLE XXIII. FILAMENTARY LAMINATE STATIC PROPERTY DATA

Material System: Boron/Epoxy Lam Orient: [0]_{3T}
 Load Orient: 0°
 Type Loading: Tension ☒, Comp ☐, Shear ☐, Interlam Shear ☐
 Type Test Specimen: Coupon: 1 x 9 in. with 1-1/2 in. Tabs
 Soak at Temp - °F for - Hr. Test Temp RT °F

Property		Batch No. 288					
		Spec Ident	1	2	3 ⁽²⁾	4 ⁽²⁾	Ave.
Stress (Ksi)	F _{pl}	115	117	112	122		117
	F _{.85}						
	F _{.70}						
	F at 2/3 ϵ_1^{ult}	123	123	106	121		118
	F _{ult}	184	177	153	180		174
Modulus E, Gx10 ⁻⁶	E or G (primary)	31.2	35.4	31.2	32.8		32.7
	E' or G' (secondary)	27.7	25.0	30.3	30.8		28.5
Strain in./in.	Proportional Limit	ϵ_1	.00410	.00400	.00360	.00420	.00395
		ϵ_2			.000670	.000800	
		ϵ_{45}					
	Ultimate	ϵ_1	.00670	.00635	.00511	.00629	.00611
		ϵ_2					
		ϵ_{45}					

No. of Plies 3 Actual Laminate Thickness .0157 to .0160(1)
Spec Laminate Thickness: Max .0162, Min .0153, Nominal .0156
Properties based on: Nominal Thickness X ; Actual Thickness

Filament Count _____/in. Void Content _____% Ply Thick. _____in.
Fil Vol Fract 0. Resin Wt Fract 0. Lam Density _____lb/in.³

Laminate: Tape or Matrix Desig 5505 Manuf Narmco
Scrim Cloth 104 Additives Used None
Cure Spec NR Spec ST0105LA0007

Comments: (1) After subtracting 0.001 in. for extra scrim balance ply
 (2) Strain-gaged

TABLE XXIV. FILAMENTARY LAMINATE STATIC PROPERTY DATA

Material System: Boron/Epoxv Lam Orient: [0]_{6T}
 Type Loading: Tension ☒, Comp ☐, Shear ☐, Interlam Shear ☐
 Type Test Specimen: Coupon, 1 x 9 in. with 1-1/2 in. Tabs
 Soak at Temp °F for Hr. Test Temp RT °F

Property		Batch No.	288					Ave.
Spec Ident		1	2	3 (2)	4 (2)			
Stress (Ksi)	F _{pl}	123	108	110	117		114	
	F _{.85}							
	F _{.70}							
	F at 2/3 ϵ_1^{ult}	128	128	130	125		127	
	F _{ult}	189	187	192	183		188	
Modulus E, Gx10 ⁻⁶	E or G (primary)	29.8	30.7	28.8	28.8		29.5	
	E' or G' (secondary)	25.0	25.0	27.0	27.9		26.2	
Strain in./in.	Proportional Limit	ϵ_1	.00440	.0037	.0039	.00410		.00403
		ϵ_2			.000850	.000850		
		ϵ_{45}						
	Ultimate	ϵ_1	.00695	.00675	.00706			.00683
		ϵ_2						
		ϵ_{45}						
No. of Plies <u>6</u> Actual Laminate Thickness <u>.0315</u> (1) Spec Laminate Thickness: Max <u>.0324</u> , Min <u>.0306</u> , Nominal <u>.0312</u> Properties based on: Nominal Thickness X ; Actual Thickness								
Filament Count <u> </u> /in. Void Content <u> </u> % Ply Thick. <u> </u> in. Fil Vol Fract <u>0.</u> Resin Wt Fract <u>0.</u> Lam Density <u> </u> lb/in. ³								
Laminate: Tape or Matrix Desig <u>5505</u> Manuf <u>Narmco</u> Scrim Cloth <u>104</u> Additives Used <u>None</u> Cure Spec <u>NR Spec ST0105LA0007</u>								

Comments: (1) After subtracting 0.001 in. for each scrim balance ply
 (2) Strain-gaged

TABLE XXV. FILAMENTARY LAMINATE STATIC PROPERTY DATA

Material System: Boron/Epoxy Lam Orient: [0/±45/0]_T
 Type Loading: Tension ☒, Comp ☐, Shear ☐, Interlam Shear ☐
 Type Test Specimen: Coupon 1 x 9 in. with 1-1/2 in. loading tabs
 Soak at Temp °F for Hr. Test Temp RT °F

Property		Batch No.						
		Spec Ident	1	2	3	4 (2)		Ave.
Stress (Ksi)	F_{pl}		50.0	52.0	53.0	47.0		50.5
	$F_{.85}$							
	$F_{.70}$							
	F at $2/3 \epsilon_1^{ult}$		67.5	66.	68.5	60.7		65.7
	F_{ult}		98.4	95.5	99.6	96.7		97.5
Modulus $E, G \times 10^{-6}$	E or G (primary)		16.4	16.6	16.5	15.0		16.1
	E' or G' (secondary)		14.0			15.0		13.5
Strain in./in.	Proportional Limit	ϵ_1	.00310	.00325	.00330	.00320		.00321
		ϵ_2				.00195		.00195
		ϵ_{45}						
	Ultimate	ϵ_1	.00640	.00625	.00655	.00625		.00636
		ϵ_2				.00390		.00390
		ϵ_{45}						
No. of Plies <u>4</u> Actual Laminate Thickness <u>.0215</u> ① Spec Laminate Thickness: Max <u>.0216</u> , Min <u>.0204</u> , Nominal <u>.0208</u> Properties based on: Nominal Thickness <u>X</u> ; Actual Thickness								
Filament Count <u> </u> /in. Void Content <u> </u> % Ply Thick. <u> </u> in. Fil Vol Fract <u>0.</u> Resin Wt Fract <u>0.</u> Lam Density <u> </u> lb/in. ³								
Laminate: Tape or Matrix Desig <u>5505</u> Manuf <u>Varmco</u> Scrim Cloth <u> </u> Additives Used <u> </u> Cure Spec <u>NR Spec ST0105LA0007</u>								

Comments: ① After subtracting 0.001 in. for extra scrim balance ply
 2 Strain-gaged

TABLE XXVI. FILAMENTARY LAMINATE STATIC PROPERTY DATA

Material System: Boron/Epoxy Lam Orient: [0/±45/0] 2T
 Load Orient: 0°
 Type Loading: Tension ☒, Comp ☐, Shear ☐, Interlam Shear ☐
 Type Test Specimen: Coupon, 1 x 9 in. with 1-1/2 in. loading tabs
 Soak at Temp - °F for - Hr. Test Temp RT °F

Property		Batch No.	288					
Spec Ident		1	2	3	4 (2)		Ave.	
Stress (Ksi)	F _{pl}	62.0	67.0	66.0	72.0		65.7	
	F _{.85}	85.5					85.5	
	F _{.70}							
	F at 2/3 ϵ_1^{ult}	67.5	66.	74.0	73.5		70.2	
	F _{ult}	88.5	101.0	106.0	104.1		99.8	
Modulus E, Gx10 ⁻⁶	E or G (primary)	18.7	15.0	16.5	16.1		16.5	
	E' or G' (secondary)		14.7	13.0			13.8	
Strain in./in.	Proportional Limit	ϵ_1	.00350	.00445	.00400	.00450		.00413
		ϵ_2				-.00320		-.00320
		ϵ_{45}						
	Ultimate	ϵ_1	.00580	.00670	.00700	.00693		.00661
		ϵ_2				-.00510		-.00510
		ϵ_{45}						
No. of Plies <u>8</u> Actual Laminate Thickness <u>.0425</u> ① Spec Laminate Thickness: Max <u>.0432</u> , Min <u>.0408</u> , Nominal <u>.0416</u> Properties based on: Nominal Thickness X ; Actual Thickness								
Filament Count <u> </u> /in. Void Content <u> </u> % Ply Thick. <u> </u> in. Fil Vol Fract <u>0.</u> Resin Wt Fract <u>0.</u> Lam Density <u> </u> lb/in. ³								
Laminate: Tape or Matrix Desig <u>5505</u> Manuf <u>Narmco</u> Scrim Cloth <u> </u> Additives Used <u> </u> Cure Spec <u>NR Spec ST0105LA0007</u>								

Comments: ① After subtracting 0.001 in. for extra scrim balance ply
 ② Strain-gaged

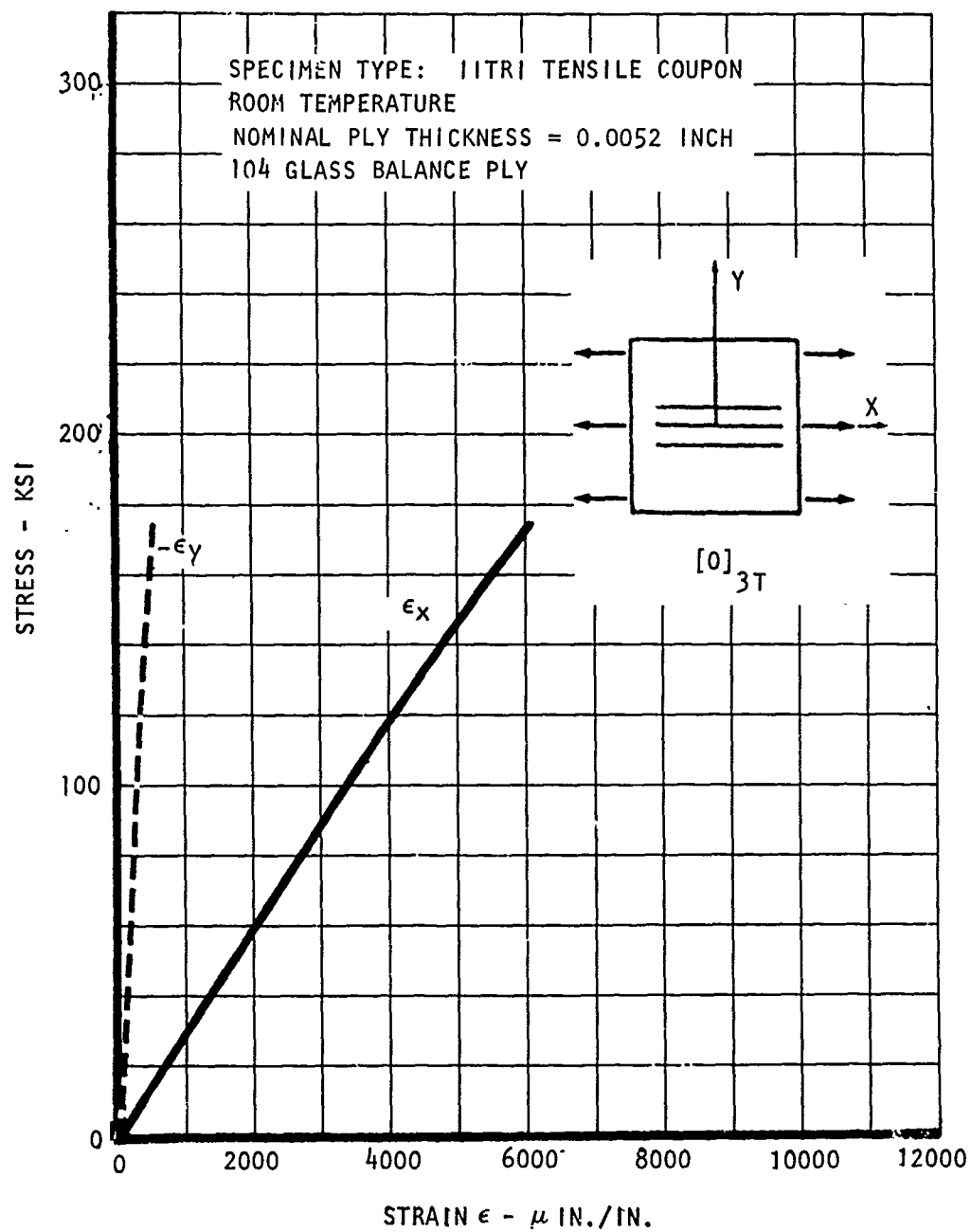


Figure 14. Longitudinal Tension - $[0]_{3T}$ Laminate

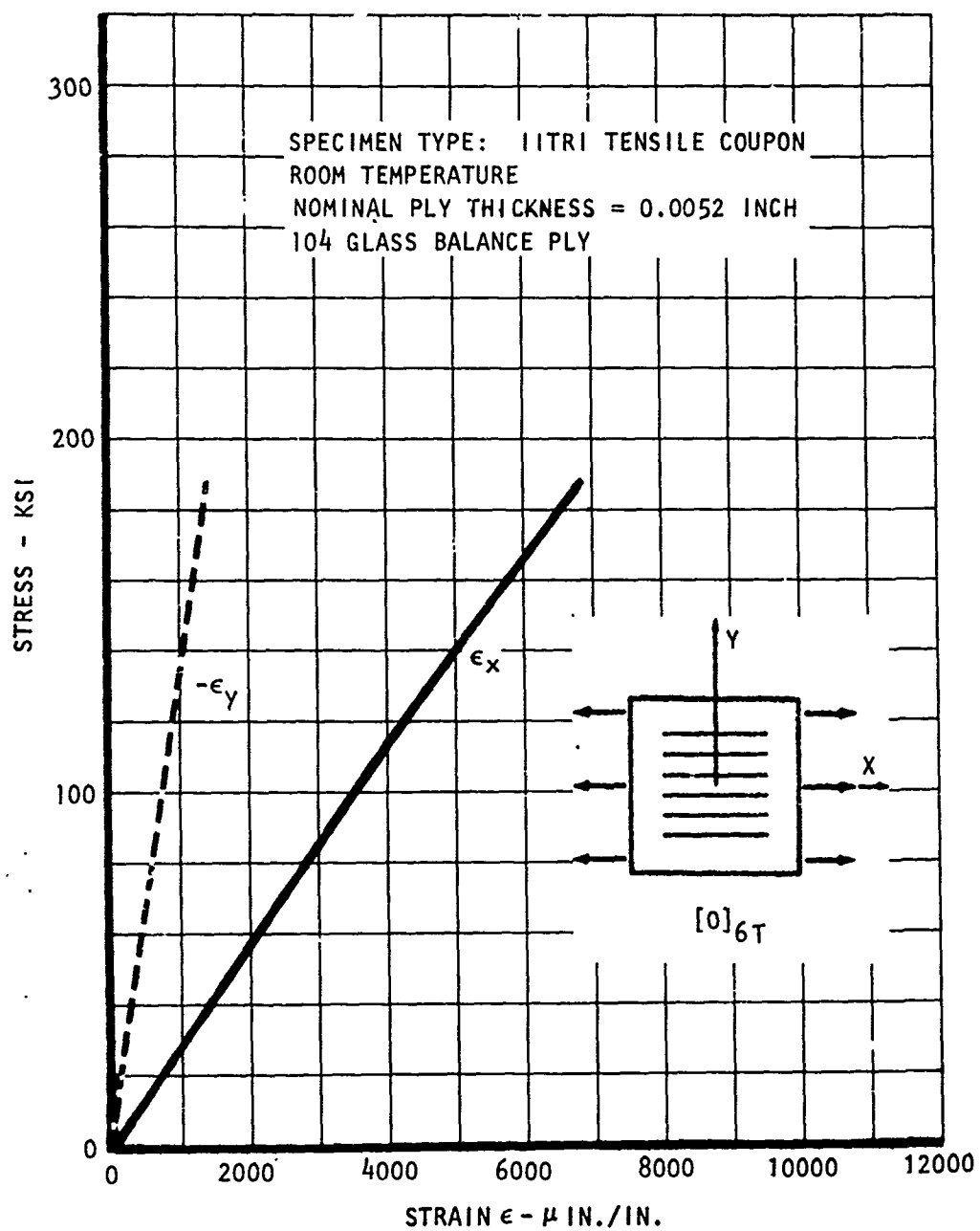


Figure 15. Longitudinal Tension - $[0]_{6T}$ Laminate

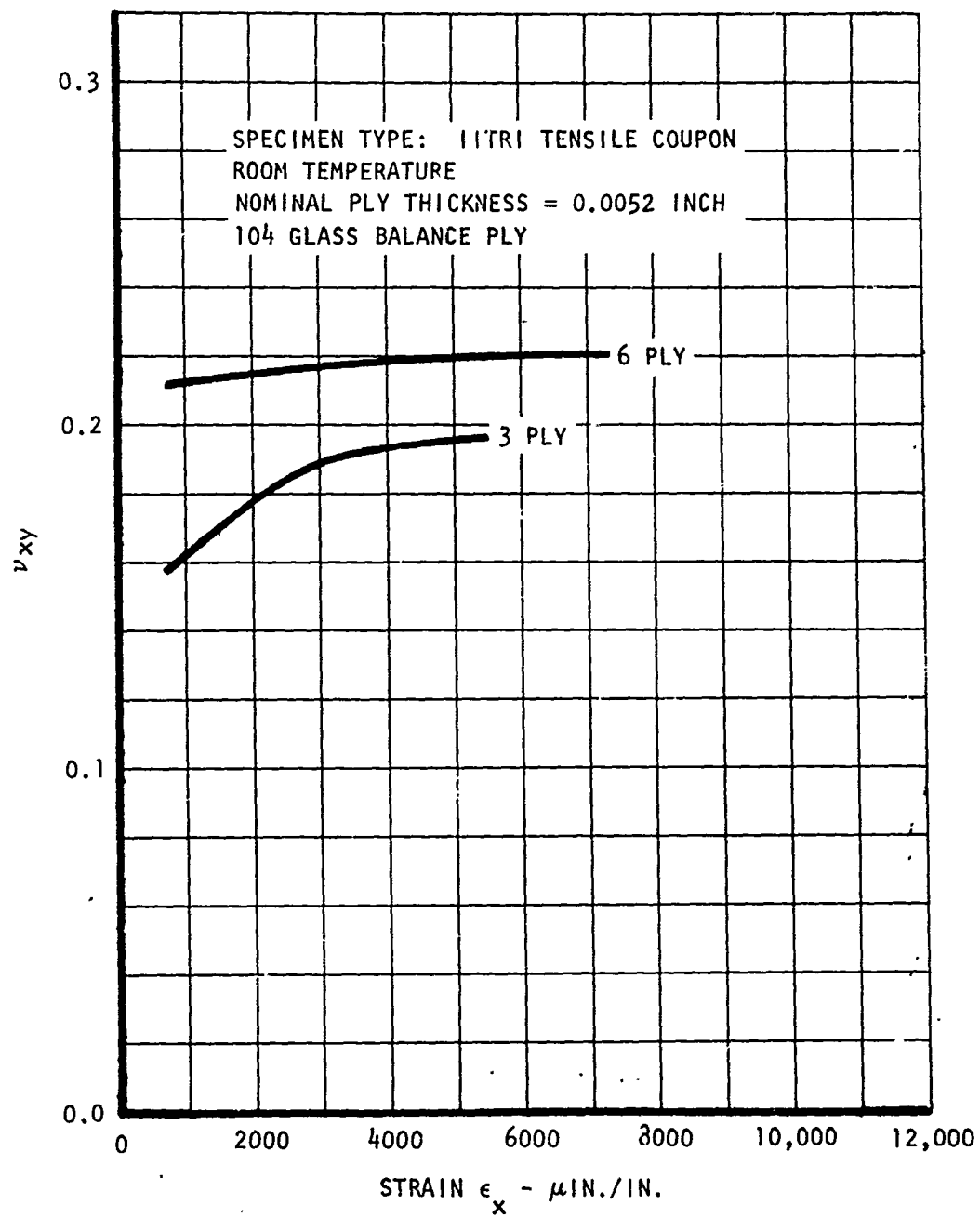


Figure 16. Poisson's Ratio ν_{xy} for $[0]_C$ Laminates

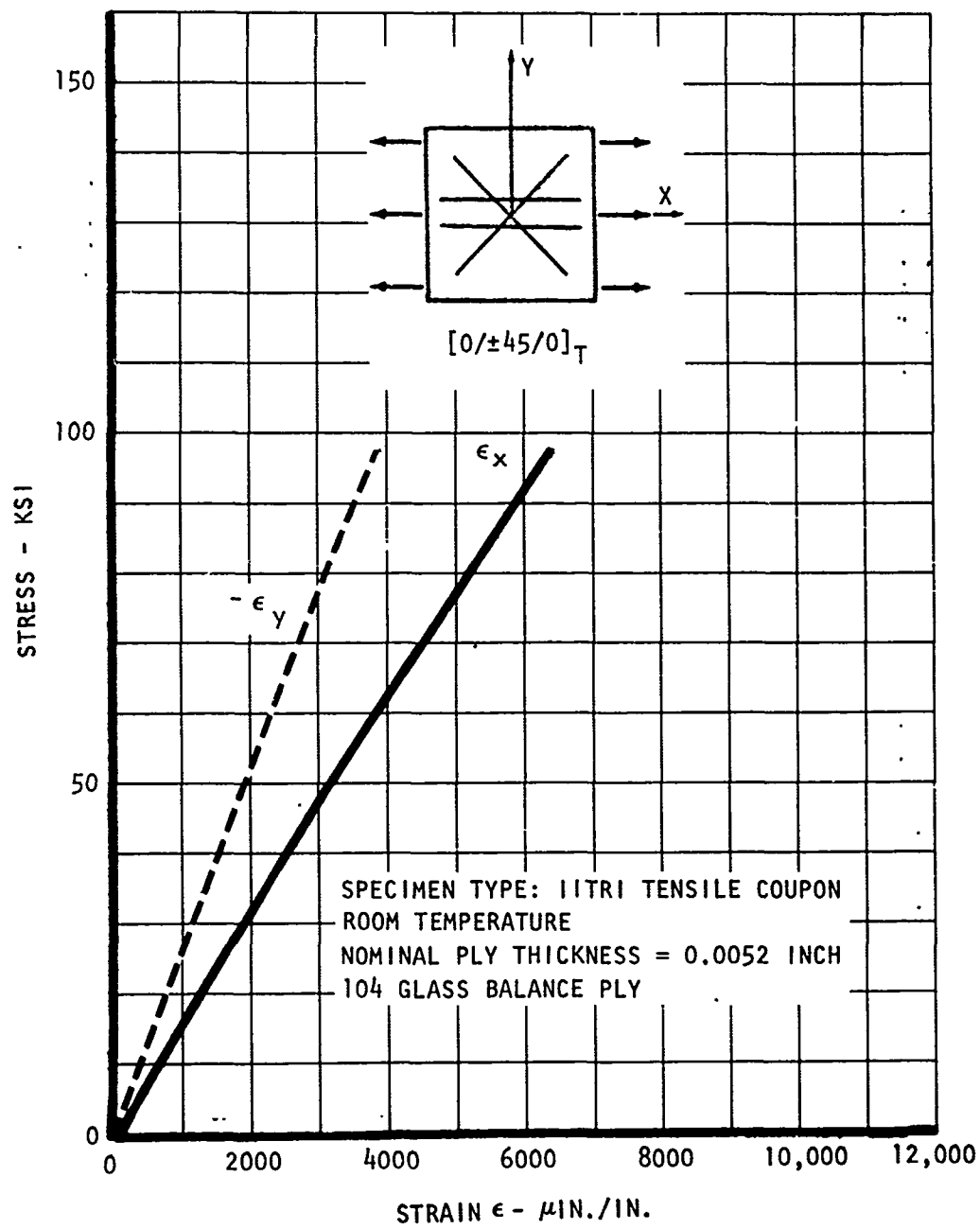


Figure 17. Longitudinal Tension - $[0/\pm 45/0]_T$ Laminate

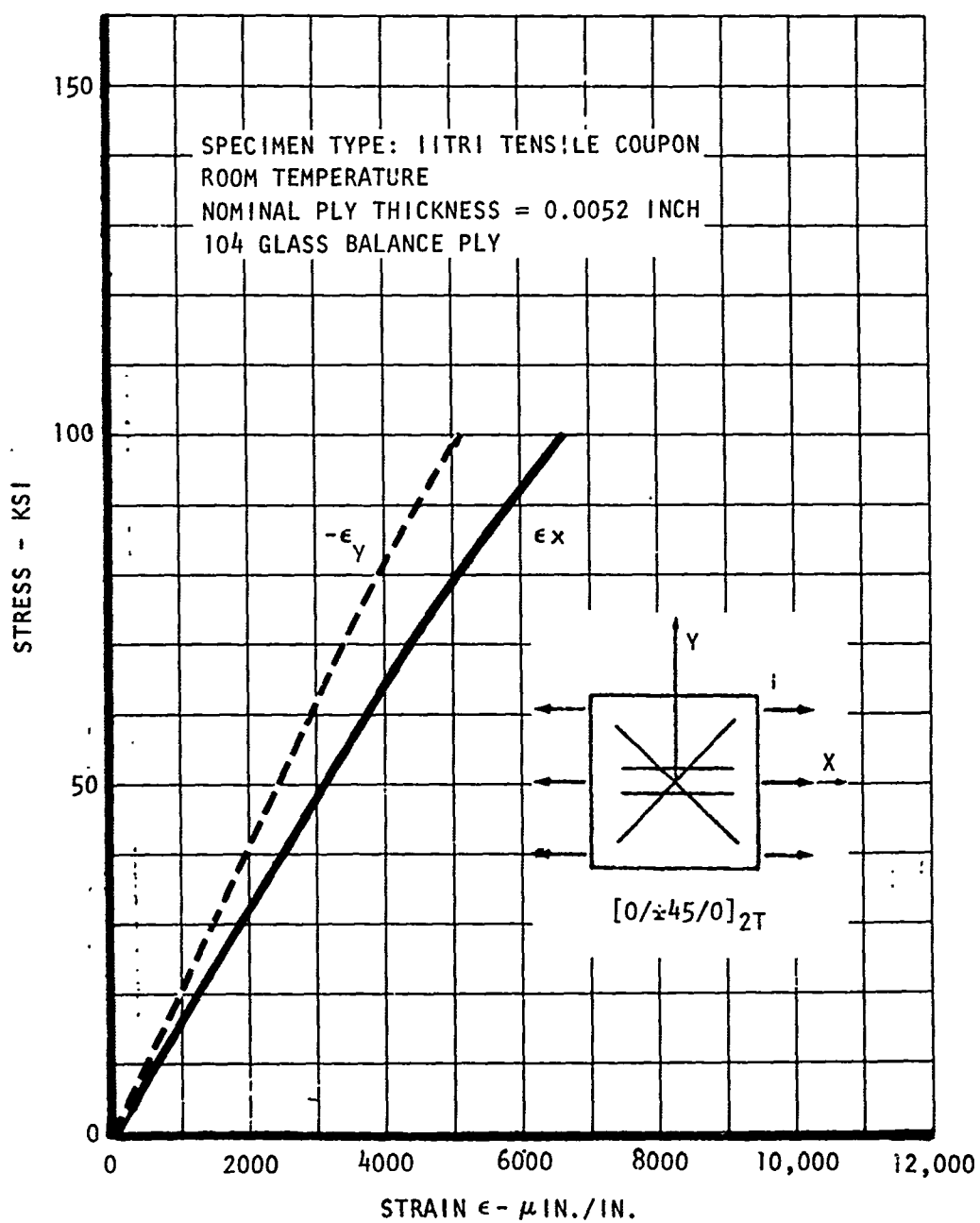


Figure 18. Longitudinal Tension $[0/\pm 45/0]_{2T}$ Laminate

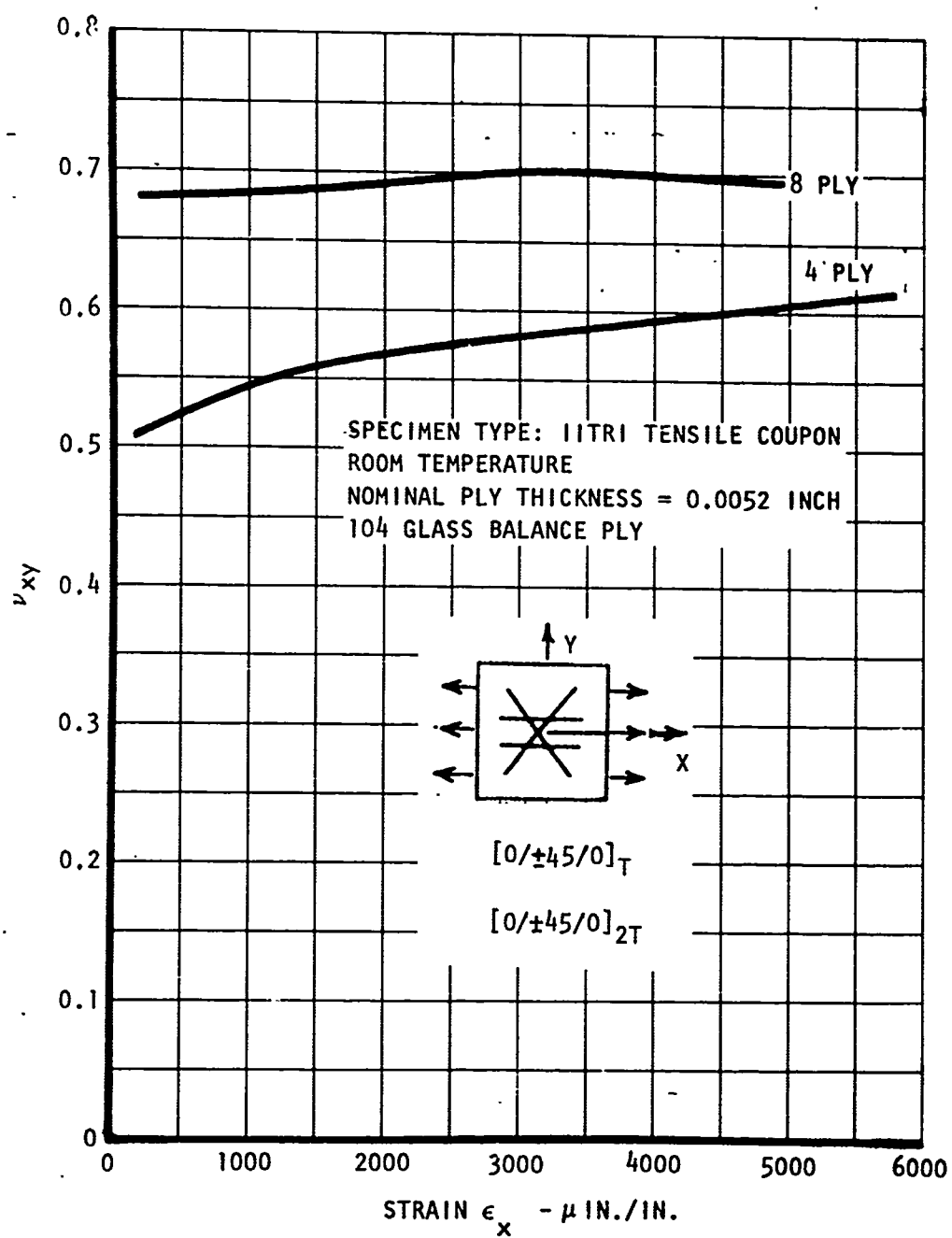


Figure 19. Poisson's Ratio ν_{xy} for $[0_2/\pm 45]_C$ Laminates

TRANSVERSE TENSILE TEST RESULTS

Transverse tensile specimen data are summarized in tables XXVII through XXX and plotted in figures 20 through 24.

A rather significant difference in failure strength exists between the three-ply $[0]_3T$ and six-ply $[0]_6T$ unidirectional specimens, with the six-ply being the stronger (8.69 versus 5.87 ksi, based on average values). However, the lowest value of the six-ply and the highest value of the three-ply specimens are nearly equal (7.45 versus 6.98 ksi). This could result from either the greater sensitivity of the thinner laminate to internal defects or to testing techniques.

A smaller difference exists in the primary modulus between the three-ply and six-ply results (2.84 versus 2.58 Msi, respectively). This may be due to the balance ply of glass scrim cloth, which would contribute more significantly to the $[0]_3T$ (four layers of scrim) than to the $[0]_6T$ (seven layers of scrim) laminate.

Transverse tensile strength of the four-ply $[0/\pm 45/0]_T$ laminate was unexpectedly higher than that of the corresponding eight-ply $[0/\pm 45/0]_{2T}$ laminate by a factor of approximately two (29.75 to 16.59 ksi average values). Consonant with the strength differential, the failure strains of the four-ply were over twice the values of the eight-ply laminate. In addition, the primary modulus of the eight-ply was higher than the four-ply laminate (4.31 to 4.00 Msi average), and the four-ply specimens evidenced a much greater degree of ductility, especially at the higher load levels. In effect, these two thicknesses of the same basic $[0/\pm 45/0]_T$ laminate family behaved as though they were from different layup orientations.

A probable explanation of this difference is indicated in figure 25, which shows the surface strains for the plies at 90 degrees to the loading. The initial failure, for all three cases shown, is in the matrix material between the filaments of the plies at 90 degrees to the applied load. When these plies are on the outside, the matrix material between filaments can elongate without appreciable biaxial stress because of its proximity to the free surface of the laminate. However, when the 0-degree plies are in the interior of the laminate, this surface relief is no longer available, and a relatively large biaxial stress (in the short transverse direction) is developed.

On the basis of this consideration, a significant reduction in strength would be expected in the four-ply material if the plies at 90 degrees to the loading were placed in the center as shown in the $[+45/0_2/-45]_T$ laminate of figure 25. Thus, the strength of this configuration of four-ply material should be close to that of the eight-ply. To evaluate this, three $[+45/0_2/-45]_T$ specimens were made and tested in transverse tension. (A moderate

TABLE XXVII. FILAMENTARY LAMINATE STATIC PROPERTY DATA

Material System: Boron/Epoxy Lam Orient: [0]_{3T}
 Type Loading: Tension ☒, Comp ☐, Shear ☐, Interlam Shear ☐
 Type Test Specimen: Coupon, 1 x 9 in. with 1-1/2 in. tabs
 Soak at Temp °F for Hr. Test Temp RT °F

Property		Batch No.	288					Ave.
Spec Ident		1	2	3	4 (2)			
Stress (Ksi)	ppl	3.15	3.3	3.25	3.1		3.20	
	F _{.85}				6.00		6.00	
	F _{.70}							
	F at 2/3 ϵ_1^{ult}	4.65	3.87	4.30	5.65		4.61	
	F _{ult}	5.75	4.85	5.90	6.98		5.87	
Modulus E, Gx10 ⁻⁶	E or G (primary)	2.95	2.80	2.75	2.87		2.84	
	E' or G' (secondary)	1.94		2.50	1.60		2.01	
Strain in./in.	Proportional Limit	ϵ_1	.00107	.00115	.0012	.00107		.00112
		ϵ_2				.000010		.00001
		ϵ_{45}						
	Ultimate	ϵ_1	.00225	.00185	.00240	.00310		.00240
		ϵ_2				.000015		.000015
		ϵ_{45}						
No. of Plies <u>3</u> Actual Laminate Thickness <u>.0160 to .0155</u> ① Spec Laminate Thickness: Max <u>.0162</u> , Min <u>.0153</u> , Nominal <u>.0156</u> Properties based on: Nominal Thickness χ ; Actual Thickness								
Filament Count <u> </u> /in. Void Content <u> </u> % Ply Thick. <u> </u> in. Fil Vol Fract <u>0.</u> Resin Wt Fract <u>0.</u> Lam Density <u> </u> lb/in. ³								
Laminate: Tape or Matrix Design <u>5505</u> Manuf <u>Narmco</u> Scrim Cloth <u>104</u> Additives Used <u>None</u> Cure Spec <u>NR Spec ST0105LA0007</u>								

Comments: ① After subtracting 0.001 in. for extra scrim balance ply
 (2) Strain-gaged

TABLE XXVIII. FILAMENTARY LAMINATE STATIC PROPERTY DATA

Material System: Boron/Epoxy Lam Orient: [0]_{6T}
 Type Loading: Tension ☒, Comp ☐, Shear ☐, Interlam Shear ☐
 Type Test Specimen: Coupon, 1 x 9 in. with 1-1/2 in. tabs
 Soak at Temp °F for Hr. Test Temp RT °F

Property		Batch No. 288						
Spec Ident		1	2	3	4 (2)		Ave.	
Stress (Ksi)	F _{P1}	4.8	4.2	4.7	4.2		4.4	
	F _{.85}		7.45		6.90		7.17	
	F _{.70}							
	F at 2/3 ϵ_1^{ult}	7.75	6.05	7.00	6.92		4.01	
	F _{ult}	9.85	7.45	8.70	8.75		8.69	
Modulus E, Gx10 ⁻⁶	E or G (primary)	2.30	2.75	2.60	2.67		2.58	
	E' or G' (secondary)	1.70	1.80	1.90	1.80		1.80	
Strain in./in.	Proportional Limit	ϵ_1	.00210	.00160	.00185	.00170		.00181
		ϵ_2				.000025		.000025
		ϵ_{45}						
	Ultimate	ϵ_1	.00487	.00325	.00380	.00400		.00398
		ϵ_2				.000040		.000040
		ϵ_{45}						

No. of Plies 6 Actual Laminate Thickness .0322 to .0315 ①
Spec Laminate Thickness: Max .0324, Min .0306, Nominal .0312
Properties based on: Nominal Thickness X ; Actual Thickness

Filament Count /in. Void Content % Ply Thick. in.
Fil Vol Fract 0. Resin Wt Fract 0. Lam Density lb/in.³

Laminate: Tape or Matrix Desig 5505 Manuf Narmco
Scrim Cloth 104 Additives Used None
Cure Spec NR Spec ST0105LA0007

Comments: ① After subtracting 0.001 in. for extra scrim balance ply
 (2) Strain-gaged

TABLE XXIX. FILAMENTARY LAMINATE STATIC PROPERTY DATA

Material System: Boron/Epoxy Lam Orient: [0/±45/0]_T
 Type Loading: Tension ☒, Comp ☐, Shear ☐, Interlam Shear ☐
 Type Test Specimen: Coupon, 1 x 9 in. with 1-1/2 in. tabs
 Soak at Temp °F for Hr. Test Temp RT °F

Property		Batch No. 288					
		Spec Ident	1	2	3	4 (2)	Ave.
Stress (Ksi.)	F _{pl}		11.4	11.0	9.2	10.0	10.4
	F _{.85}					25.10	25.10
	F _{.70}						
	F at 2/3 ϵ_1^{ult}		22.0	27.0	23.0	25.6	24.4
	F _{ult}		26.6	32.8	28.8	30.8	29.7
Modulus E, G x 10 ⁻⁶	E or G (primary)		4.40	3.60	4.20	3.80	4.00
	E' or G' (secondary)				3.00		3.00
Strain in./in.	Proportional Limit	ϵ_1	.00248	.00270	.00215	.00235	.00242
		ϵ_2				.000475	.000475
		ϵ_{45}					
	Ultimate	ϵ_1	.00680	.00980	.00760	.00890	.00828
		ϵ_2				.00157	.00157
		ϵ_{45}					
No. of Plies <u>4</u> Actual Laminate Thickness <u>.0215 to .0210</u> ① Spec Laminate Thickness: Max <u>.0216</u> , Min <u>.0204</u> , Nominal <u>.0208</u> Properties based on: Nominal Thickness χ ; Actual Thickness							
Filament Count <u> </u> /in. Void Content <u> </u> % Ply Thick. <u> </u> in. Fil Vol Fract <u>0.</u> Resin Wt Fract <u>0.</u> Lam Density <u> </u> lb/in. ³							
Laminate: Tape or Matrix Desig <u>5505</u> Manuf <u>Narmco</u> Scrim Cloth <u> </u> Additives Used <u> </u> Cure Spec <u>NR Spec ST0105LA0007</u>							

Comments: ① After subtracting 0.001 in. for extra scrim balance ply
 (2) Strain-gaged

TABLE XXX. FILAMENTARY LAMINATE STATIC PROPERTY DATA

Material System: Boron/Epoxy Lam Orient: [0/±45/0]_{2T}
 Type Loading: Tension ☒, Comp ☐, Shear ☐, Interlam Shear ☐
 Type Test Specimen: Coupon, 1 x 9 in. with 1-1/2 in. tabs
 Soak at Temp - °F for - Hr. Test Temp RT °F

Property		Batch No. 288					
		Spec Ident	2	3	4 (2)	1	Ave.
Stress (Ksi)	ρ_{pl}		10.5	8.1	10.0	10.2	9.7
	$F_{.85}$						
	$F_{.70}$						
	F at $2/3 \epsilon_1^{ult}$		12.48	13.67	13.90	12.90	13.24
	F^{ult}		16.25	16.85	16.85	16.40	16.57
Modulus $E, G \times 10^{-6}$	E or G (primary)		4.00	4.80	4.50	3.95	4.31
	E' or G' (secondary)		3.70	4.10	4.00	3.70	3.87
Strain in./in.	Proportional Limit	ϵ_1	.00253	.00166	.00200	.00250	.00217
		ϵ_2			.000430		.000430
		ϵ_{45}					
	Ultimate	ϵ_1	.00410	.00397	.00395	.00430	.00408
		ϵ_2			.000700		.000700
		ϵ_{45}					
No. of Plies <u>8</u> Actual Laminate Thickness <u>.0423 to .0415</u> ① Spec Laminate Thickness: Max <u>.0432</u> , Min <u>.0408</u> , Nominal <u>.0416</u> Properties based on: Nominal Thickness <u>X</u> ; Actual Thickness							
Filament Count <u> </u> /in. Void Content <u> </u> % Ply Thick. <u> </u> in. Fil Vol Fract <u>0.</u> Resin Wt Fract <u>0.</u> Lam Density <u> </u> lb/in. ³							
Laminate: Tape or Matrix Desig <u>5505</u> Manuf <u>Narmco</u> Scrim Cloth <u> </u> Additives Used <u> </u> Cure Spec <u>NR Spec ST0105LA0007</u>							

Comments: ① After subtracting 0.001 in. for extra scrim balance ply

② Strain-gaged

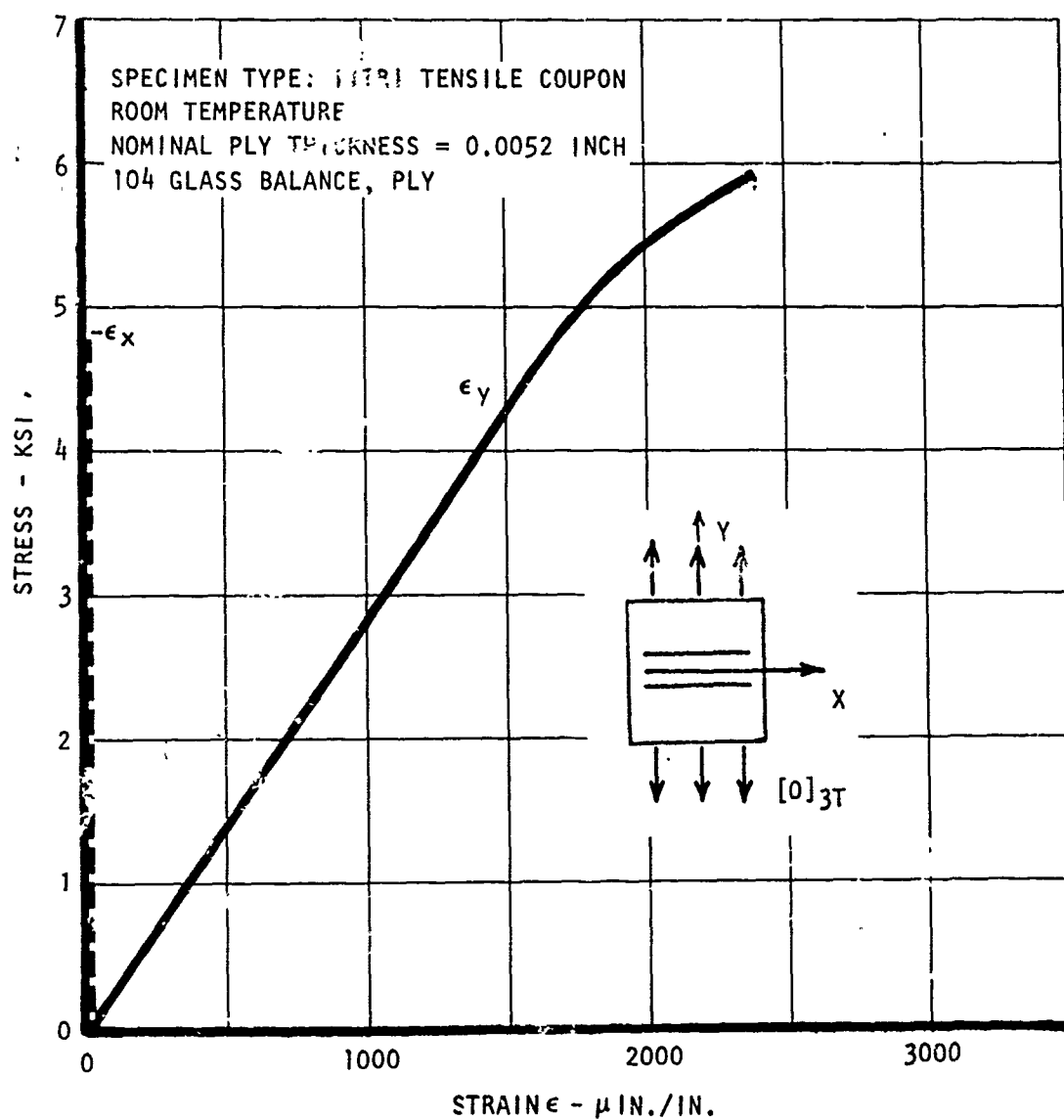


Figure 20. Transverse Tension - $[0]_{3T}$ Laminate

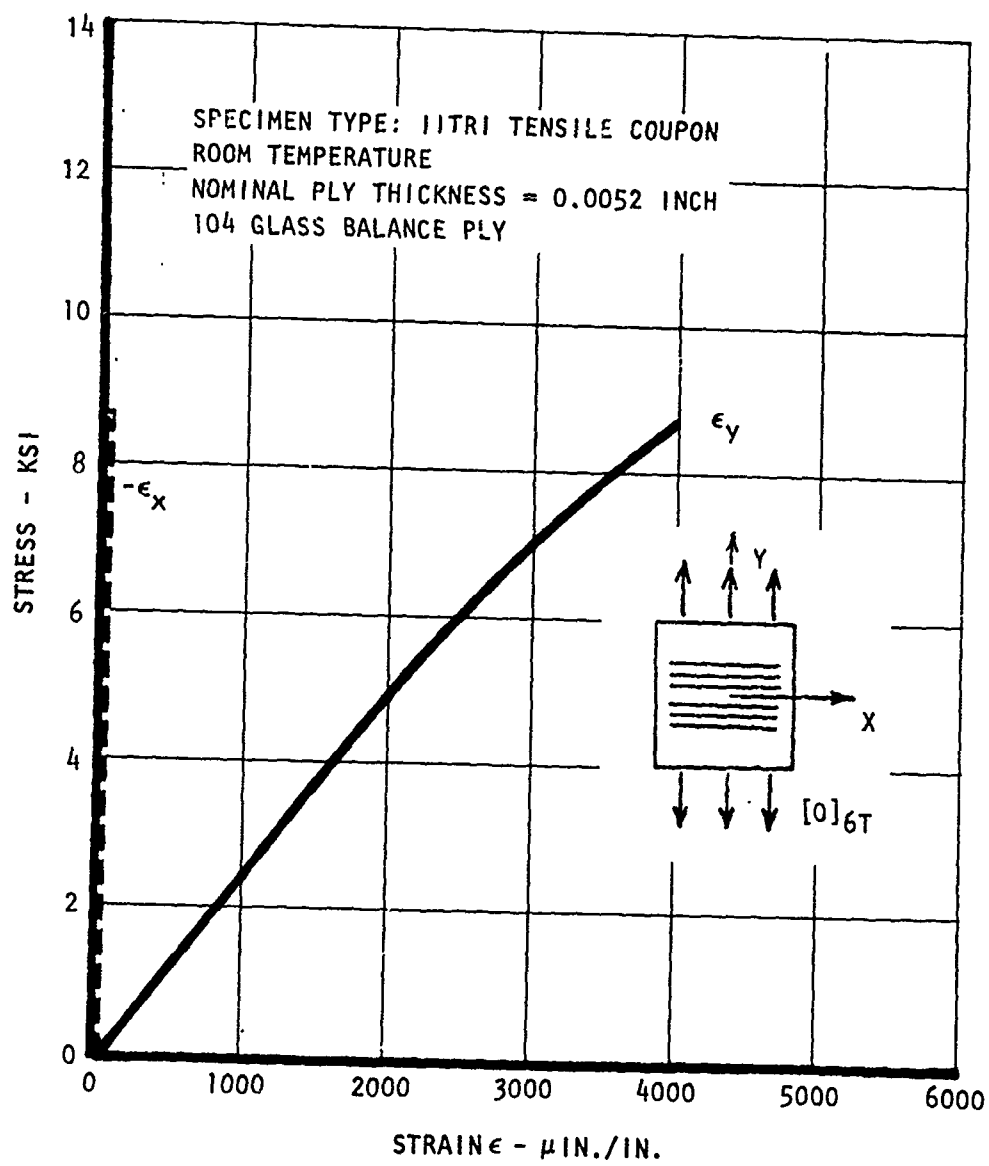


Figure 21. Transverse Tension - $[0]_{6T}$ Laminate

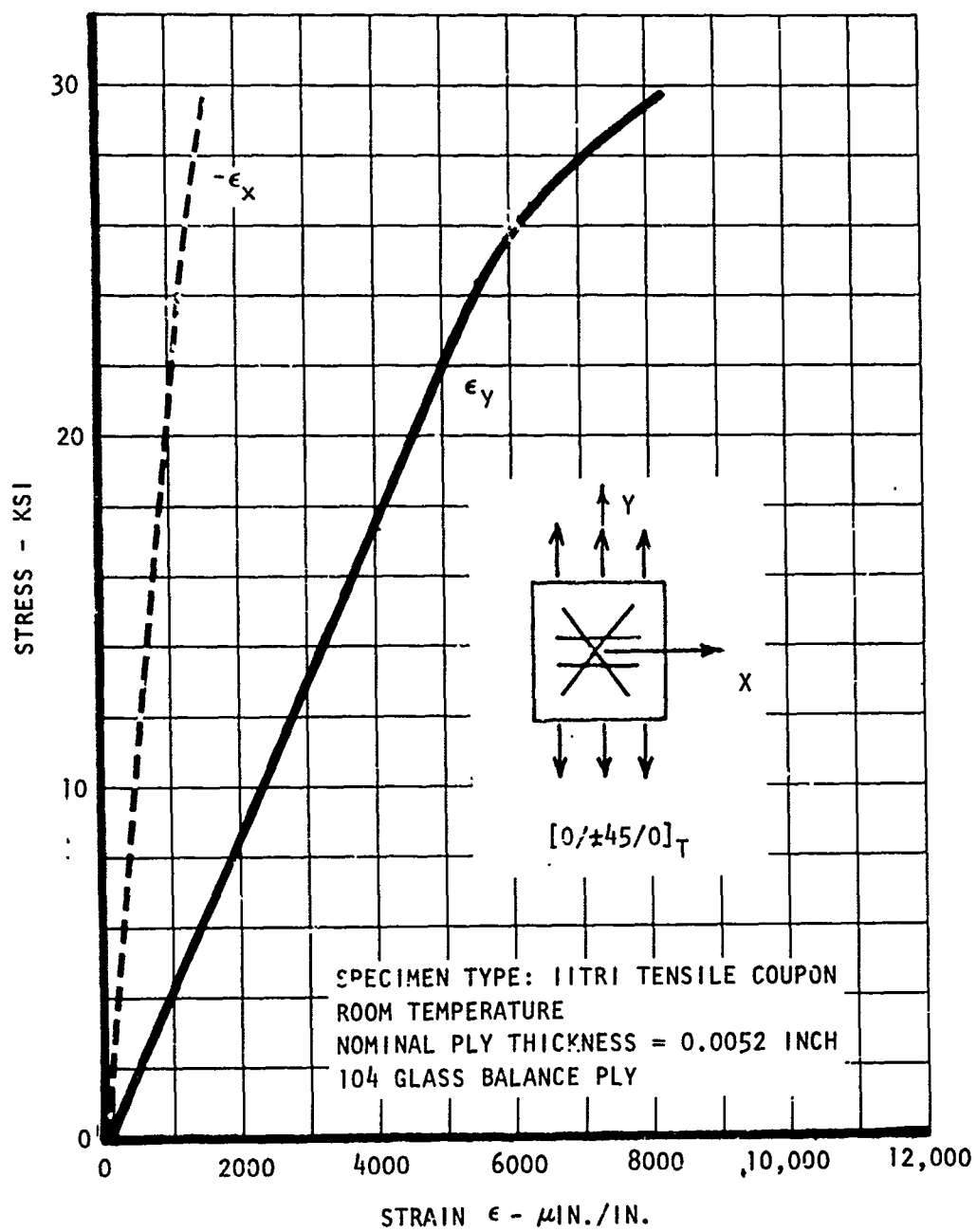


Figure 22. Transverse Tension - $[0/\pm 45/0]_T$ Laminate

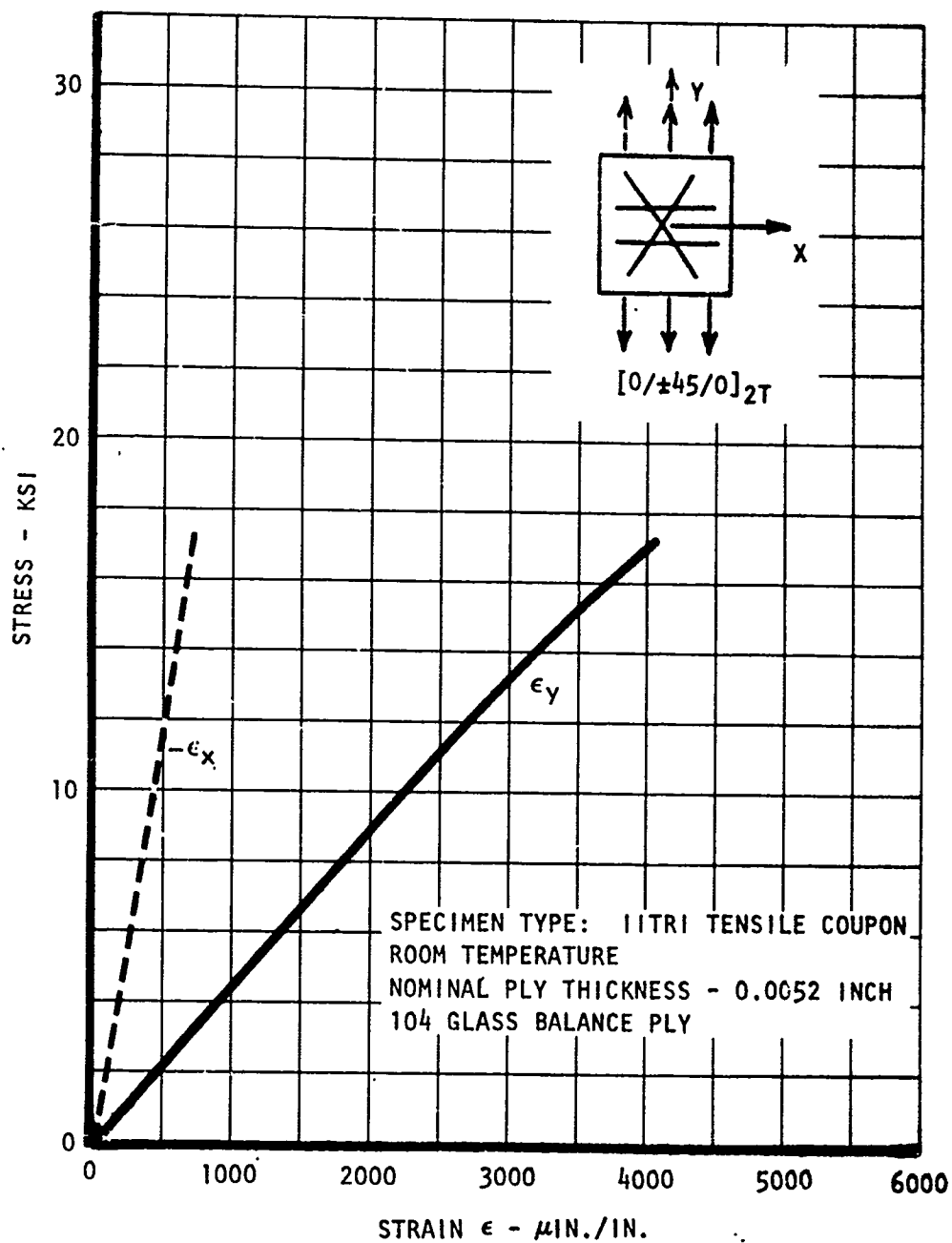


Figure 23. Transverse Tension - [0/+45/0]_{2T} Laminate

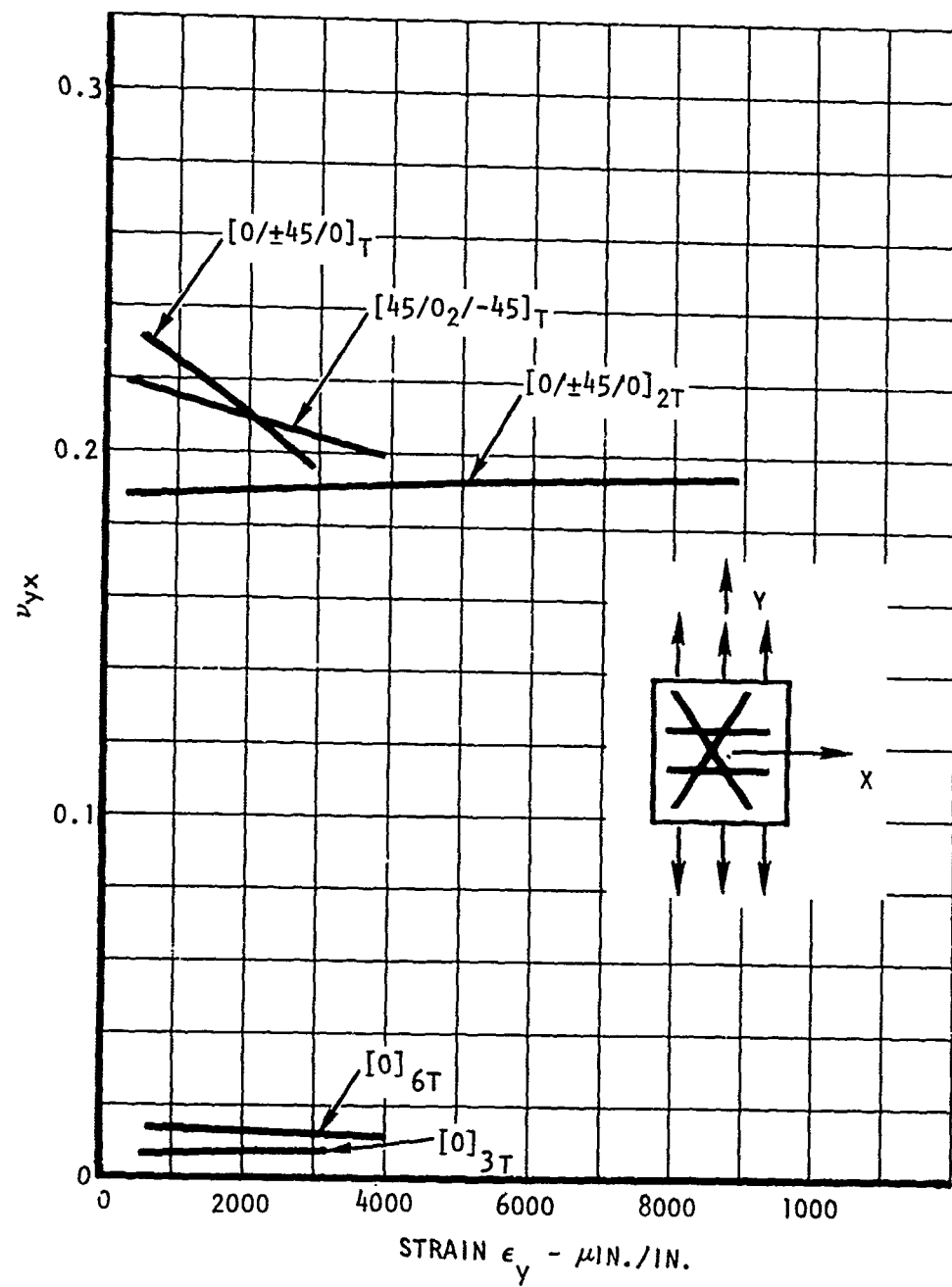


Figure 24. Poisson's Ratio ν_{yx} for $[0]_C$ and $[0_2/\pm 45]_C$ Laminates

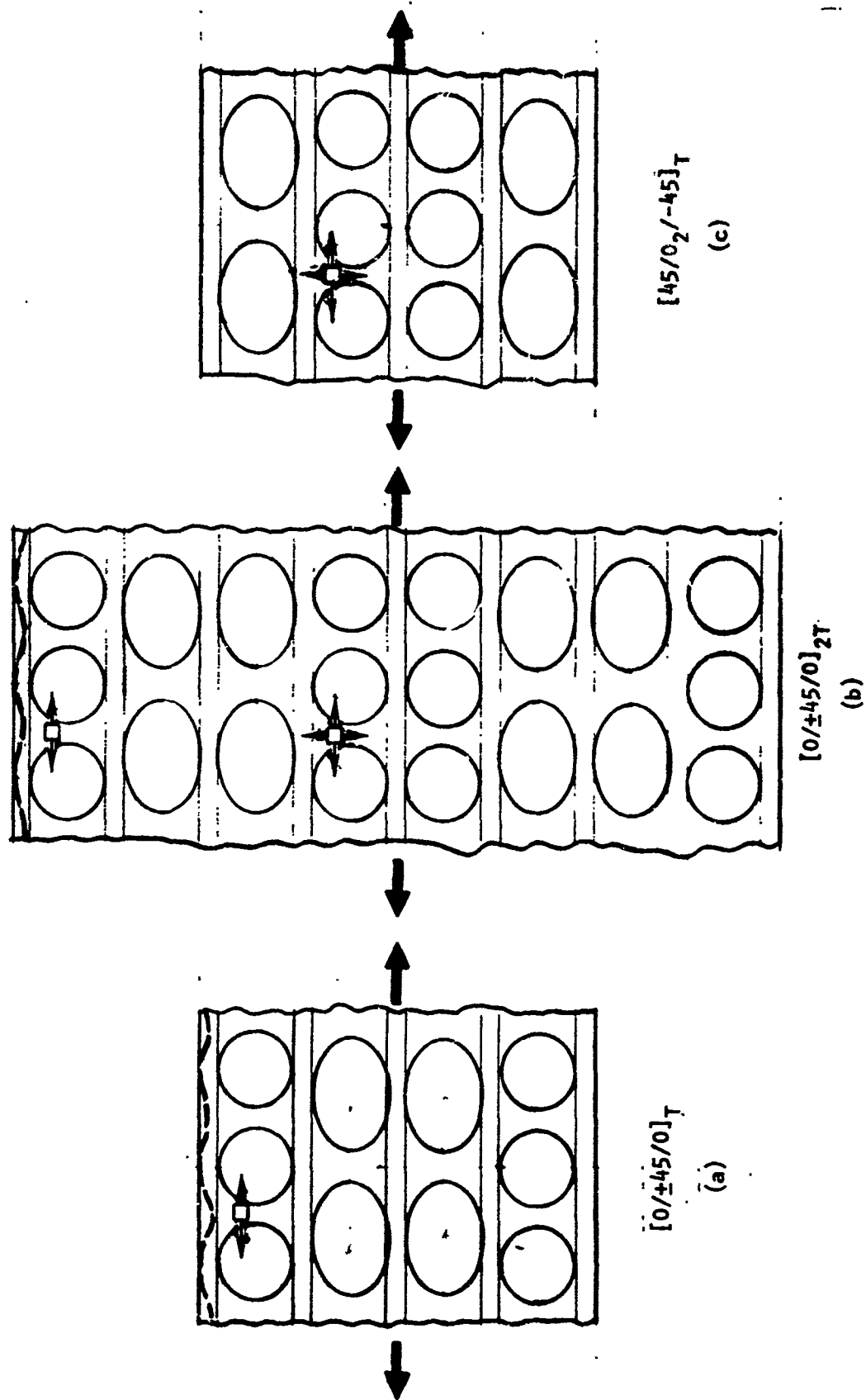


Figure 25. Surface and Subsurface Matrix Effects on Plies 90° to Loading Direction.

amount of warpage was experienced, as expected, but did not affect the tests.) Results are given in table XXXII and figure 26. A comparison of strengths and failing elongations is given in table XXXI.

TABLE XXXI. FAILING STRENGTH AND STRAINS COMPARISON FOR $[0_2/\pm 45]_C$ LAMINATES

Laminate	Plies	Failing Stress F_{ty}^{tu} (ksi)	Failing Strain ϵ_y^{tu} (in./in.)
$[0/\pm 45/0]_T$	4	29.7	0.00828
$[0/\pm 45/0]_{2T}$	8	16.5	0.00408
$[+45/0_2/-45]_T$	4	12.5	0.00270

It is noted that the failing stress of the special four-ply laminate with the interior plies transverse to the loading was indeed reduced, even below that of the eight-ply laminate. This is felt to confirm the existence of the surface relief for the $[0/\pm 45/0]_T$. In addition, it indicates the presence of a ply sequence sensitivity even to membrane-type loading. As a result of this sensitivity, the four-ply laminate $[0/\pm 45/0]_T$ was considered unsuitable for use in the element test program.

LONGITUDINAL COMPRESSION BEAM TEST RESULTS

A modified beam bending specimen for use in determining laminate compression allowables was designed to avoid the cost and difficulties reported to exist from use of the bonded metal loading blocks (reference 11). This configuration, shown in figure 27, depends on a resin-filled core section for support of the loading pin and load distribution into the core. A thin layer of spacer material separates the resin filler from the compression test laminate face to avoid excessive stiffening and flattening in this area. Maximum bearing stress (estimated for a six-ply unidirectional compression face) is a relatively low value of about 3,000 psi, well within the capability of the resin filler material.

A single prototype beam specimen was fabricated and tested to evaluate the practicality of this design. Some "air bubble" voids were present in the core-filled zone as shown in figure 28, but these were considered acceptable and did not affect the test.

The face sheet chosen for the verification test was the $[0]_{6T}$ laminate, since this would generate the highest pin loadings and core shear loadings. Specimen failure occurred at a laminate stress level of 510,000 psi (filament stress of 1,015,000 psi). This result is considerably higher than those

TABLE XXXII. FILAMENTARY LAMINATE STATIC PROPERTY DATA

Material System: Boron/Epoxy Lam Orient: [+45/0₂/-45]_T

Type Loading: Tension ☒, Comp ☐, Shear ☐, Interlam Shear ☐

Type Test Specimen: Coupon, 1 x 9 in. with 1-1/2 in. loading tabs

Soak at Temp - °F for - Hr. Test Temp RT °F

Property		Batch No. 288					
		Spec Ident	1	2	3 (2)		Ave.
Stress (Ksi)	F _{P1}		6.7	5.9	7.0		6.6
	F _{.85}						
	F _{.70}						
	F at 2/3 ϵ_1^{ult}		9.0	7.9	8.2		8.3
	F _{ult}		13.7	11.7	12.1		12.5
Modulus E, G x 10 ⁻⁶	E or G (primary)		4.85	4.90	4.50		4.75
	E' or G' (secondary)		4.30	4.40	4.10		4.26
Strain in./in.	Proportional Limit	ϵ_1	.00137	.00120	.00152		.00136
		ϵ_2			.000325		.000325
		ϵ_{45}					
	Ultimate	ϵ_1	.00290	.00250	.00270		.00270
		ϵ_2			.000560		.000560
		ϵ_{45}					

No. of Plies 4 Actual Laminate Thickness .0215 ①

Spec Laminate Thickness: Max .0216, Min .0204, Nominal .0208

Properties based on: Nominal Thickness \times ; Actual Thickness

Filament Count - /in. Void Content - % Ply Thick. - in.

Fil Vol Fract 0. Resin Wt Fract 0. Lam Density - lb/in.³

Laminate: Tape or Matrix Desig 5505 Manuf Narmco

Scrim Cloth - Additives Used -

Cure Spec NR Spec ST0105LA0007

Comments: ① After subtracting 0.001 in. for extra scrim balance ply

② Strain-gaged

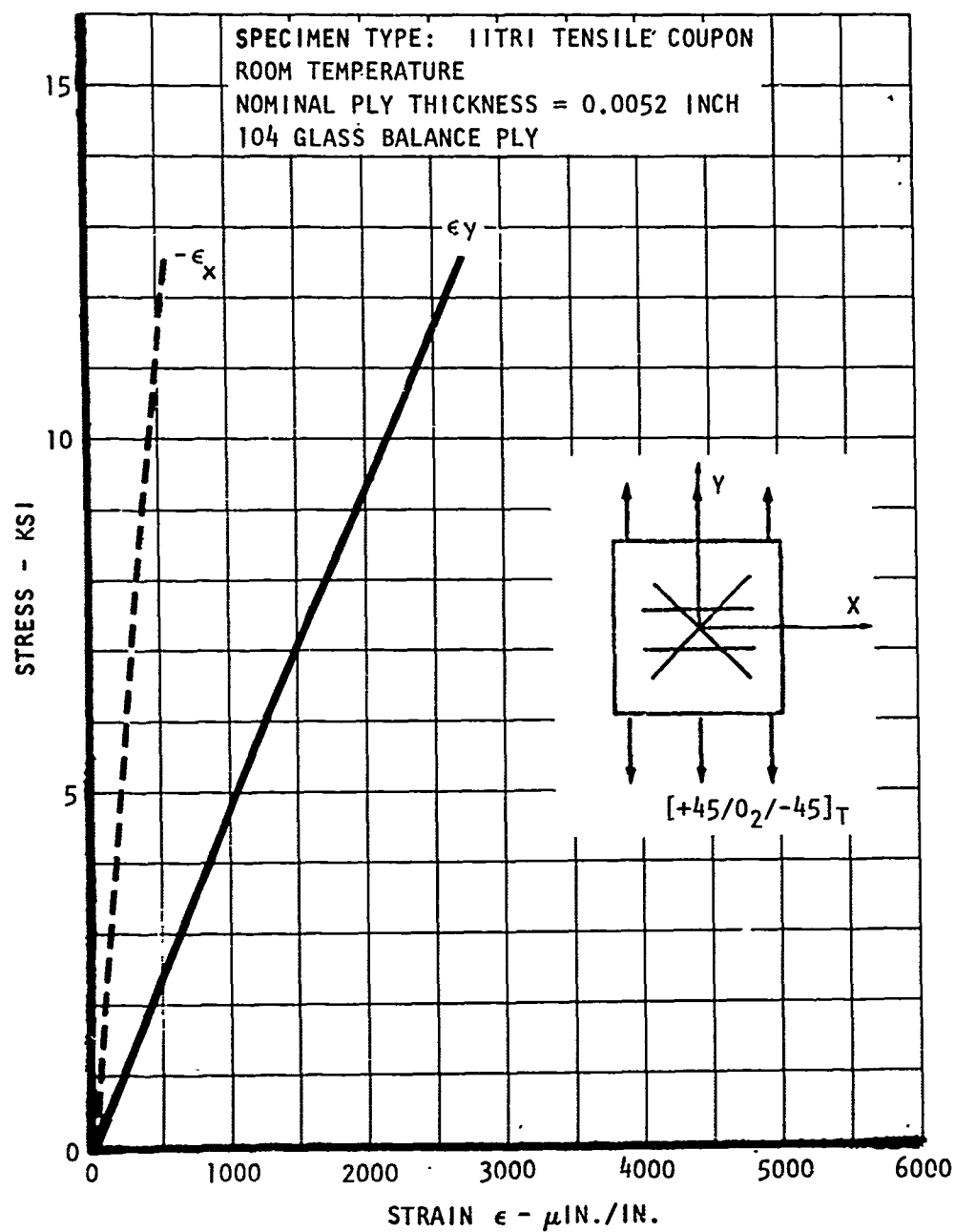


Figure 26. Transverse tension $-[+45/0_2/-45]_T$ Laminate

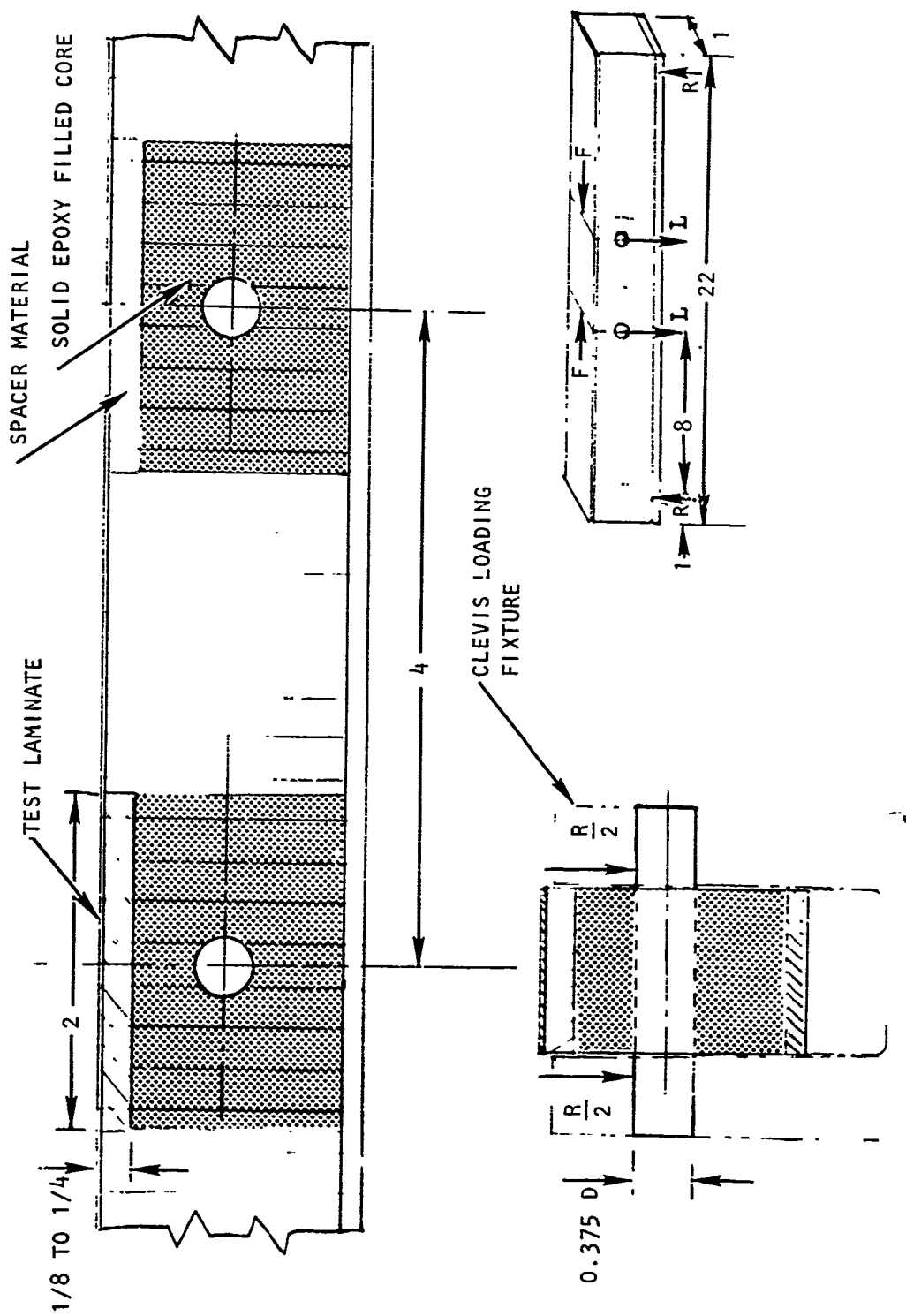


Figure 27. Laminate Compression beam bending Test Specimen

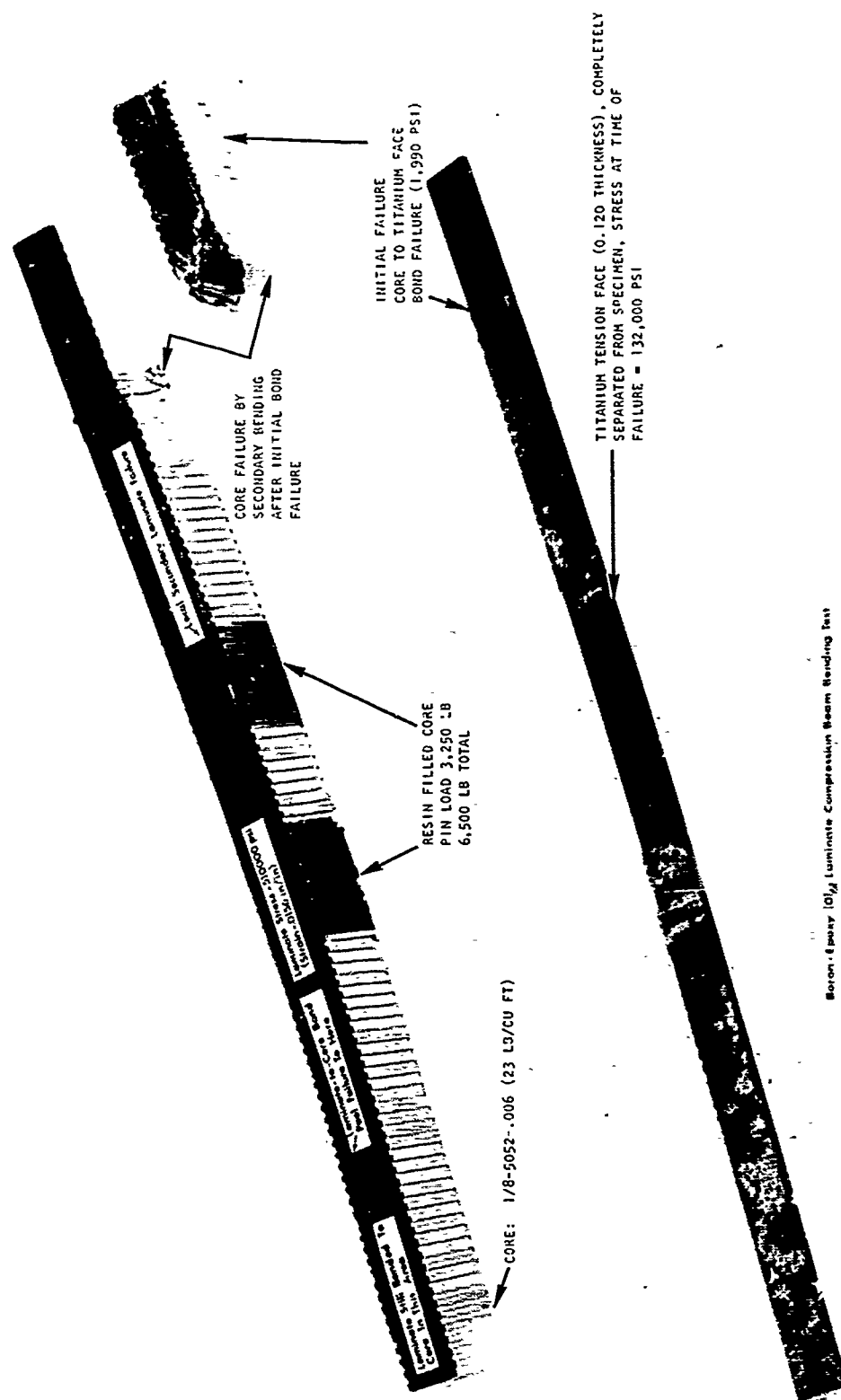
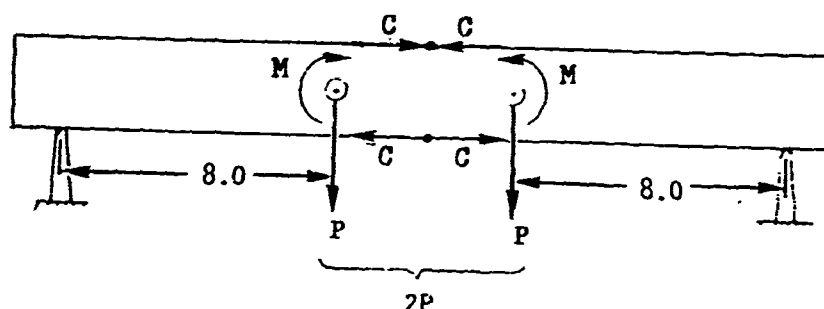
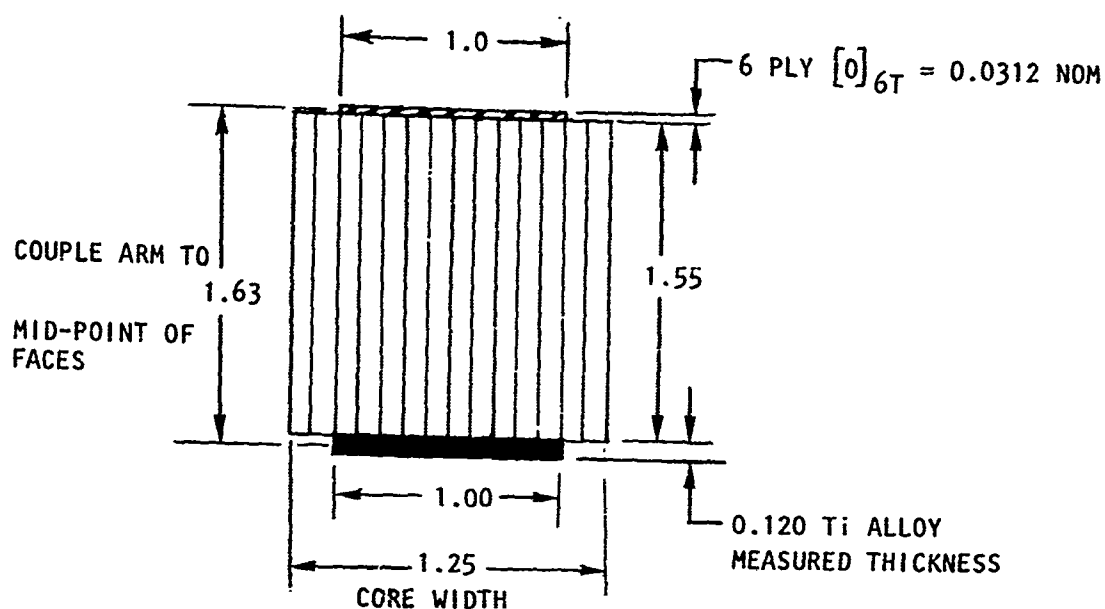


Figure 28. Failed Compression Beam Test Specimen



BEAM BENDING MOMENT $M = 8P$

FACE SHEET COUPLE LOAD $C = 8P/1.63 = 4.91P$

LAMINATE STRESS $\sigma_c = 4.91P/0.0312 = 157P$

At Failure: $P = 3250$ LBS

Composite Stress : $\sigma_c = -(157)(3250) = -510,000$ psi

Resin Stress : $\sigma_m = -8000$ psi (at $\epsilon_x = 0.015$ in/in)

Filament Stress : $\sigma_f = -1,015,000$ psi

Core Shear : Adjacent to face = 1,990 psi ($W = 1.00$)
At mid-height = 1,590 psi ($W = 1.25$)

Titanium Face : 132,000 psi

Figure 29. Bending Beam Failing Stress Calculation

reported in reference 1. Calculations of laminate stress and stresses in other elements are shown in figure 29.

Beam failure did not originate in the composite face but rather is considered to have started with a core-to-titanium face bond shear failure near one of the end supports. After failure, the composite face remained undamaged except for a small flexural fracture at one edge caused by laminate bending from a secondary peeling action. This is illustrated in figure 28.

Since the design of the beam specimen was considered to be satisfactory, the remaining specimens were fabricated and tested in the same manner. A summary of the failing stress, modulus, and method of failure is shown in table XXXIII.

TABLE XXXIII. LONGITUDINAL COMPRESSION BEAM - ULTIMATE STRESS AND MODULUS SUMMARY

Laminate	Specimen	Ultimate Stress (Compression) (ksi)	Modulus (Msi)	Failure Location
[0] ₃ T	1	415	31.46	Laminate
	2	551		Laminate
[0] ₆ T	1	510	29.36	Bond
	2	523		Laminate
[0/±45/0]T	1	330	18.43	Laminate
		338		Laminate
[0/±45/0]2T	1	342	14.28	Laminate
	2	352		Laminate

Results of the tests were remarkably consistent between laminates of the same thickness and also between the two thicknesses of the same type laminate. The only exception was specimen 1 of the [0]₃T configuration, which fell significantly below all the other unidirectional failing stresses. During the test of this specimen, it was noticed that a larger than ordinary number of edge-located filaments debonded from the laminate, forming independent splinters. The failure of this specimen evidenced somewhat more general splintering than the other unidirectional specimen failures. A possible reason for this may be the variability of the resin fillet formed by the excess core-to-face adhesive along the edge of the laminate. Where present, this fillet was a strong restraint against the lateral buckling of the longitudinal edge filaments.

Another item of interest is the difference in modulus between the thin and thick laminates of the same orientation. This is attributed to the lateral load induced by (the Poisson's ratio effect of) the core. On the thinner gages, the lateral load would have a greater influence, resulting in an apparent increase in longitudinal modulus. This is most apparent in the $[0_2/\pm 45]_C$ laminates.

Of major interest is the very high compressive strengths of laminates when fully stabilized by the heavy core. Failures were typical of ultimate material compressive strength, rather than the stability-induced failure found by edgewise compressive tests on lighter core. The data in table XXXIV illustrate this difference.

TABLE XXXIV. LONGITUDINAL COMPRESSION BEAM - FAILURE STRESS
VERSUS CORE DENSITY

Laminate	Core	Type Specimen	F_{cu} (ksi)	Mode of Failure
$[0]_{6T}$	23 lb/ft ³	Beam	517	Ult comp
$[0]_{6T}$	4.5 lb/ft ³	Edge comp	128	Face wrinkle
$[0/\pm 45/0]_{2T}$	23 lb/ft ³	Beam	348	Ult comp
$[0/\pm 45/0]_{2T}$	4.5 lb/ft ³	Edge comp	152	Face wrinkle

This indicates the importance of providing adequate laminate stabilization if the higher compressive strengths are to be achieved.

Data sheets and stress-strain plots (based on strain gage data) from the compression beam specimens are presented in tables XXXV through XXXVIII and in figures 30 through 33.

Failure modes and locations are depicted in the photographs, figure 28 and figures 34 through 37. Failures in all cases initiated in the composite laminate, except for the prototype $[0]_{6T}$ specimens, which experienced initial failure in the core-to-titanium face bond.

SHEAR MODULUS TEST RESULTS

Tensile specimens to provide data for calculating the in-plane shear modulus of unidirectional material were cut at 45 degrees from the $[0]_{3T}$ and $[0]_{6T}$ panels. The results of these specimens are shown in table XXXIX and figure 38 for the three-ply material and in table XL and figure 39 for the six-ply material. These results should be used with caution, since the validity of this test method has been shown to be questionable.

TABLE XXXV. FILAMENTARY LAMINATE STATIC PROPERTY DATA

Material System: Boron/Epoxy Lam Orient: [0]3T
 Load Orient: 0°
 Type Loading: Tension ☐, Comp ☒, Shear ☐, Interlam Shear ☐
 Type Test Specimen: Sandwich Beam, 1 in. wide x 1.55 in. deep x 22 in. long
 Soak at Temp --- °F for --- Hr. Test Temp R.T. °F

Property		Batch No. 288					
		Spec Ident	1 (1)	2			Ave.
Stress (ksi)	F _{P1}		152				152
	F _{.85}		---				---
	F _{.70}		---				---
	F at 2/3 ϵ_1^{ult}		---				---
	F _{ult}		415	551			485
Modulus E, Gx10 ⁻⁶	E or G (primary)		31.4				31.4
	E' or G' (secondary)						
Strain in./in.	Proportional Limit	ϵ_1	-.00430				-.00430
		ϵ_2	+.00220				+.00220
		ϵ_{45}					
	Ultimate	ϵ_1	---				---
		ϵ_2	---				---
		ϵ_{45}					

No. of Plies 3 Actual Laminate Thickness _____
 Spec Laminate Thickness: Max .0162, Min .0153, Nominal .0156
 Properties based on: Nominal Thickness X ; Actual Thickness

Filament Count _____ /in. Void Content _____ % Ply Thick. _____ in.
 Fil Vol Fract 0. Resin Wt Fract 0. Lam Density _____ lb/in.³

Laminate: Tape or Matrix Desig 5505 Manuf Narmco
 Scrim Cloth 104 Additives Used None
 Cure Spec NR Spec ST0105LA0007

Comments: (1) Strain-gaged

TABLE XXXVI. FILAMENTARY LAMINATE STATIC PROPERTY DATA

Material System: Boron/Epoxy Lam Orient: [0] 6T
 Type Loading: Tension ☐, Comp ☒, Shear ☐, Interlam Shear ☐
 Type Test Specimen: Sandwich Beam, 1 in. wide x 1.55 in. deep x 22 in. long
 Soak at Temp - °F for - Hr. Test Temp RT °F

Property		Batch No. 288					
Spec Ident		1 (1)	2				Ave.
Stress (Ksi)	F_{pl}	410					410
	$F_{.85}$						
	$F_{.70}$						
	F at $2/3 \epsilon_1^{ult}$	340					340
	F_{ult}	510	523				516
Modulus $E, G \times 10^{-6}$	E or G (primary)	29.3					29.3
	E' or G' (secondary)	27.6					27.6
Strain in./in.	Proportional Limit	ϵ_1	-.01220				-.01220
		ϵ_2	+.00500				+.00500
		ϵ_{45}					
	Ultimate	ϵ_1	-.01560				-.01560
		ϵ_2					
		ϵ_{45}					
No. of Plies <u>6</u> Actual Laminate Thickness _____ Spec Laminate Thickness: Max <u>.0324</u> , Min <u>.0306</u> , Nominal <u>.0312</u> Properties based on: Nominal Thickness X ; Actual Thickness							
Filament Count _____ /in. Void Content _____ % Ply Thick. _____ in. Fil Vol Fract <u>0.</u> Resin Wt Fract <u>0.</u> Lam Density _____ lb/in. ³							
Laminate: Tape or Matrix Desig <u>5505</u> Manuf <u>Narmco</u> Scrim Cloth <u>104</u> Additives Used <u>None</u> Cure Spec <u>NR Spec ST0105LA0007</u>							

Comments: (1) Strain-gaged

TABLE XXXVII. FILAMENTARY LAMINATE STATIC PROPERTY DATA

Material System: Boron/Epoxy Lam Orient: [0/±45/0]_T
 Type Loading: Tension ☐, Comp ☒, Shear ☐, Interlam Shear ☐
 Type Test Specimen: Sandwich Beam, 1 in. wide x 1.55 in. deep x 22 in. long
 Soak at Temp - °F for - Hr. Test Temp RT °F

Property		Batch No. 288						
		Spec Ident	1 (1)	2				Ave.
Stress (Ksi)	F _{p1}		234					234
	F _{.85}		---					---
	F _{.70}		---					---
	F at 2/3 ϵ_1^{ult}		----					---
	F _{ult}		330	338				334
Modulus E, Gx10 ⁻⁶	E or G (primary)		18.4					18.4
	E' or G' (secondary)		16.2					16.2
Strain in./in.	Proportional Limit	ϵ_1	-.01230					-.01230
		ϵ_2	+.01100					+.01100
		ϵ_{45}						
	Ultimate	ϵ_1	---					---
		ϵ_2	---					---
		ϵ_{45}						
No. of Plies <u>4</u> Actual Laminate Thickness _____ Spec Laminate Thickness: Max <u>.0216</u> , Min <u>.0204</u> , Nominal <u>.0208</u> Properties based on: Nominal Thickness <u>X</u> ; Actual Thickness _____								
Filament Count _____ /in. Void Content _____ % Ply Thick. _____ in. Fil Vol Fract <u>0.</u> Resin Wt Fract <u>0.</u> Lam Density _____ lb/in. ³								
Laminate: Tape or Matrix Desig <u>5505</u> Manuf <u>Narmco</u> Scrim Cloth _____ Additives Used _____ Cure Spec <u>NR Spec ST0105LA0007</u>								

Comments: (1) Strain-gaged

TABLE XXXVIII. FILAMENTARY LAMINATE STATIC PROPERTY DATA

Material System: Boron/Epoxy Lam Orient: [0/±45/0]_{2T}
 Type Loading: Tension ☐, Comp ☒, Shear ☐, Interlam Shear ☐
 Type Test Specimen: Sandwich Beam, 1 in. wide x 1.55 in. deep x 22 in. long
 Soak at Temp - °F for - Hr. Test Temp RT °F

Property		Batch No. 288					
		Spec Ident	1 ⁽¹⁾	2			Ave.
Stress (Ksi)	F _{P1}		200				200
	F _{.85}		---				---
	F _{.70}		---				---
	F at 2/3 ϵ_1^{ult}		---				---
	F _{ult}		342	352			347
Modulus E, Gx10 ⁻⁶	E or G (primary)		14.2				14.2
	E' or G' (secondary)		13.9				13.9
Strain in./in.	Proportional Limit	ϵ_1	-.00950				-.00950
		ϵ_2	+.00800				+.00800
		ϵ_{45}					
	Ultimate	ϵ_1	----				---
		ϵ_2	----				---
		ϵ_{45}					
No. of Plies <u>8</u> Actual Laminate Thickness _____ Spec Laminate Thickness: Max <u>.0432</u> , Min <u>.0408</u> , Nominal <u>.0416</u> Properties based on: Nominal Thickness x ; Actual Thickness							
Filament Count _____/in. Void Content _____ % Ply Thick. _____ in. Fil Vol Fract <u>0.</u> Resin Wt Fract <u>0.</u> Lam Density _____ lb/in. ³							
Laminate: Tape or Matrix Desig <u>5505</u> Manuf <u>Narmco</u> Scrim Cloth _____ Additives Used _____ Cure Spec <u>NR Spec ST0105LA0007</u>							

Comments: (1) Strain-gaged

SPECIMEN TYPE: BEAM BENDING
 (COMPRESSIVE) ROOM TEMPERATURE
 NOMINAL PLY THICKNESS = 0.0052 IN
 104 GLASS BALANCE PLY

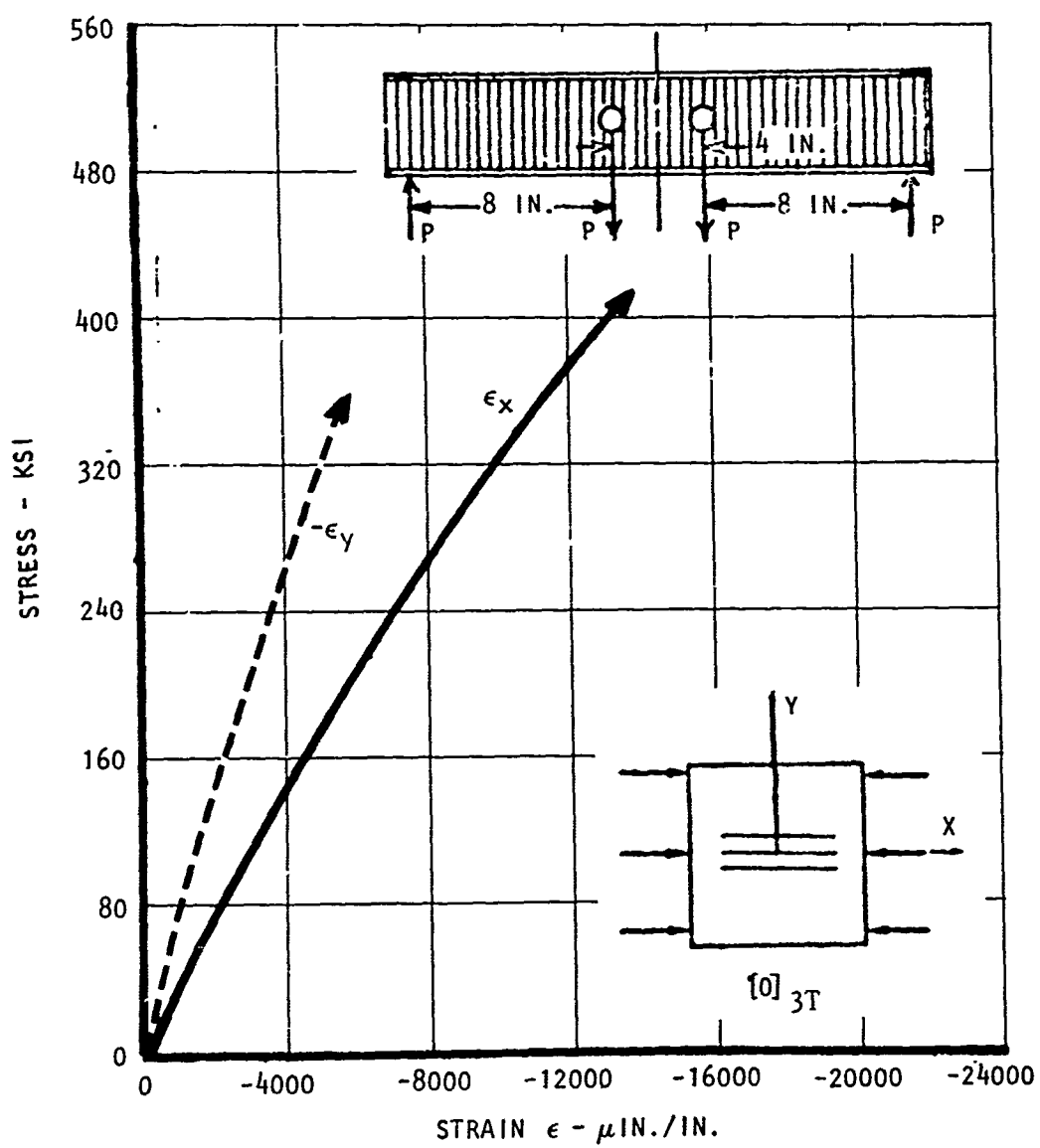


Figure 30. Compression Stress-Strain Curve for $[0]_{3T}$ Laminate

SPECIMEN TYPE: BEAM BENDING
(COMPRESSIVE) ROOM TEMPERATURE
NOMINAL PLY THICKNESS = 0.0052 IN.
104 GLASS BALANCE PLY

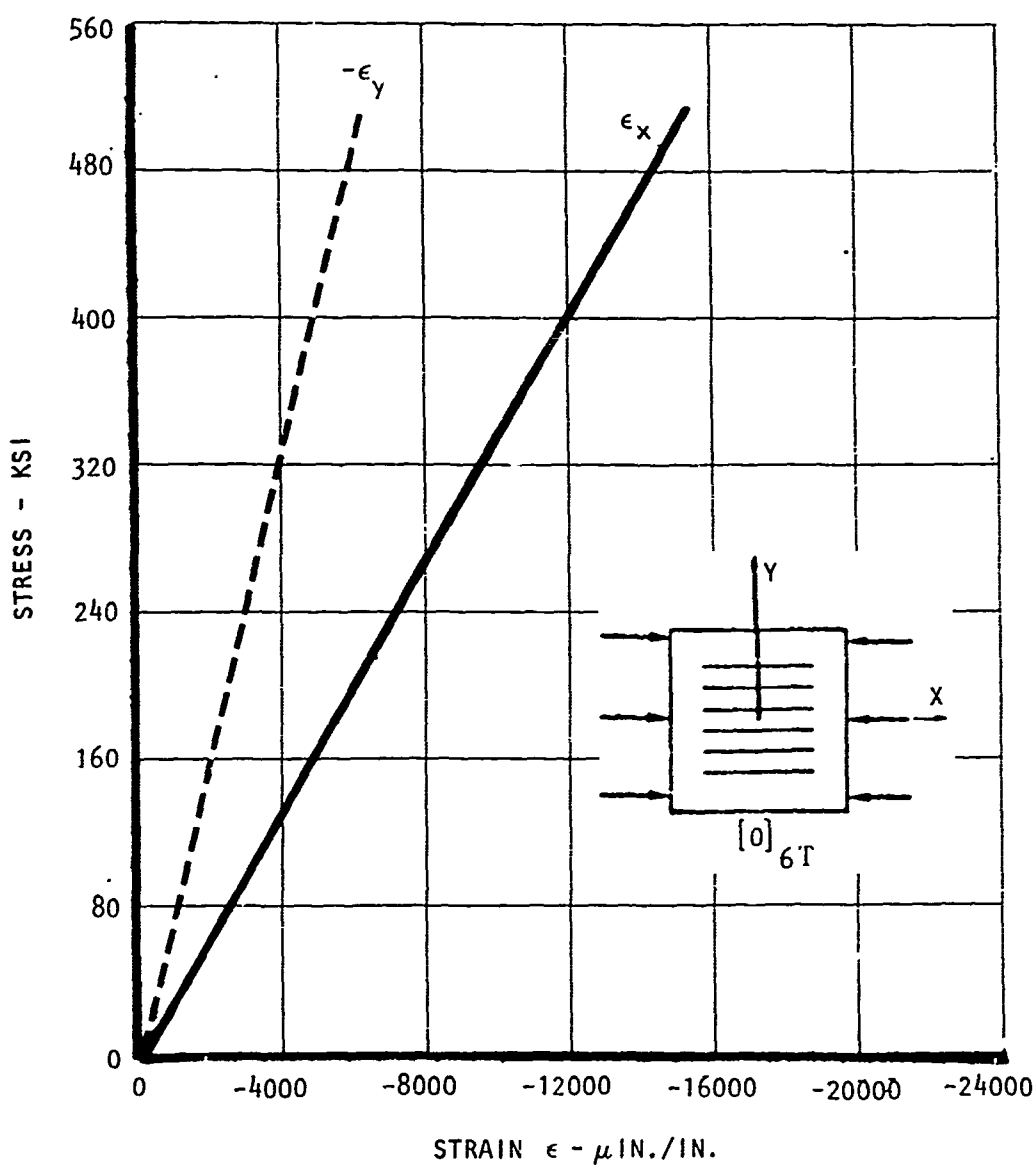
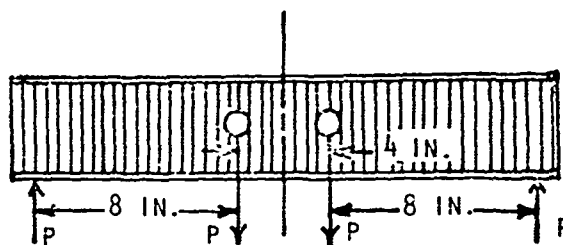


Figure 31. Longitudinal Compression - $[0]_6T$ Laminate

SPECIMEN TYPE: BEAM BENDING
(COMPRESSIVE) ROOM TEMPERATURE
NOMINAL PLY THICKNESS = 0.0052 IN.
104 GLASS BALANCE PLY

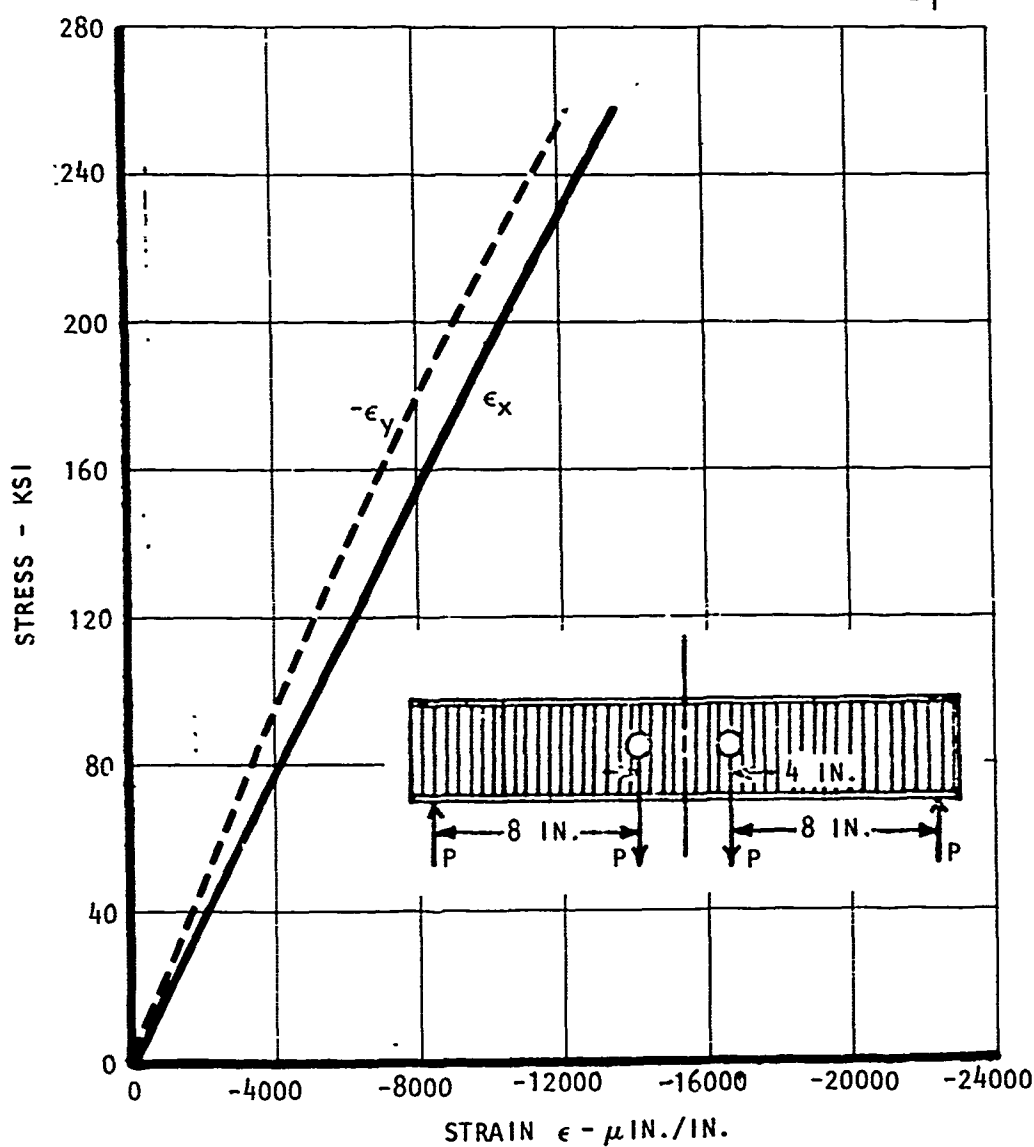
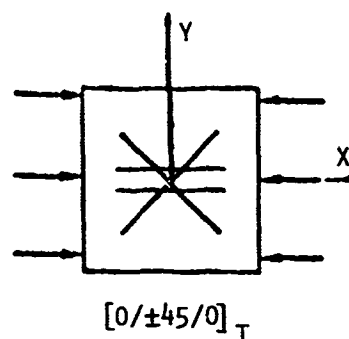


Figure 32. Compression Stress-Strain Curve for $[0/\pm 45/0]_T$ Laminate

SPECIMEN TYPE: BEAM BENDING
(COMPRESSIVE) ROOM TEMPERATURE
NOMINAL PLY THICKNESS = 0.0052 IN.
104 GLASS BALANCE PLY

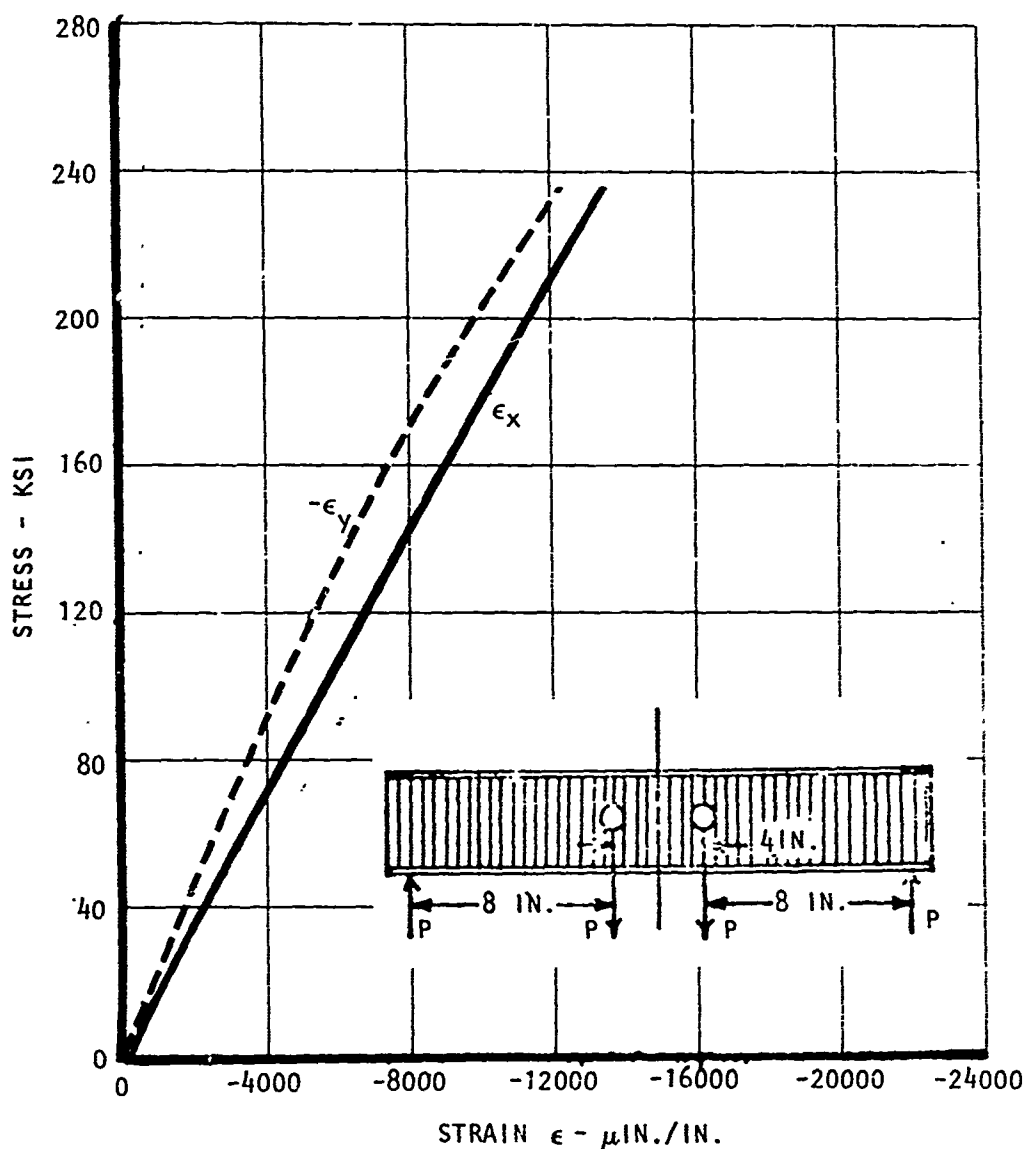
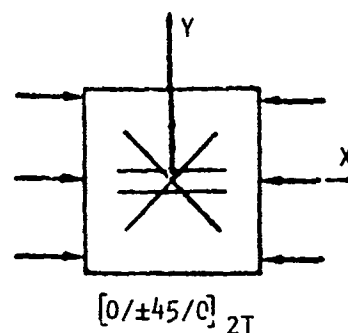


Figure 33. Compression Stress-Strain Curve for $[0/\pm 45/0]_{2T}$ Laminate

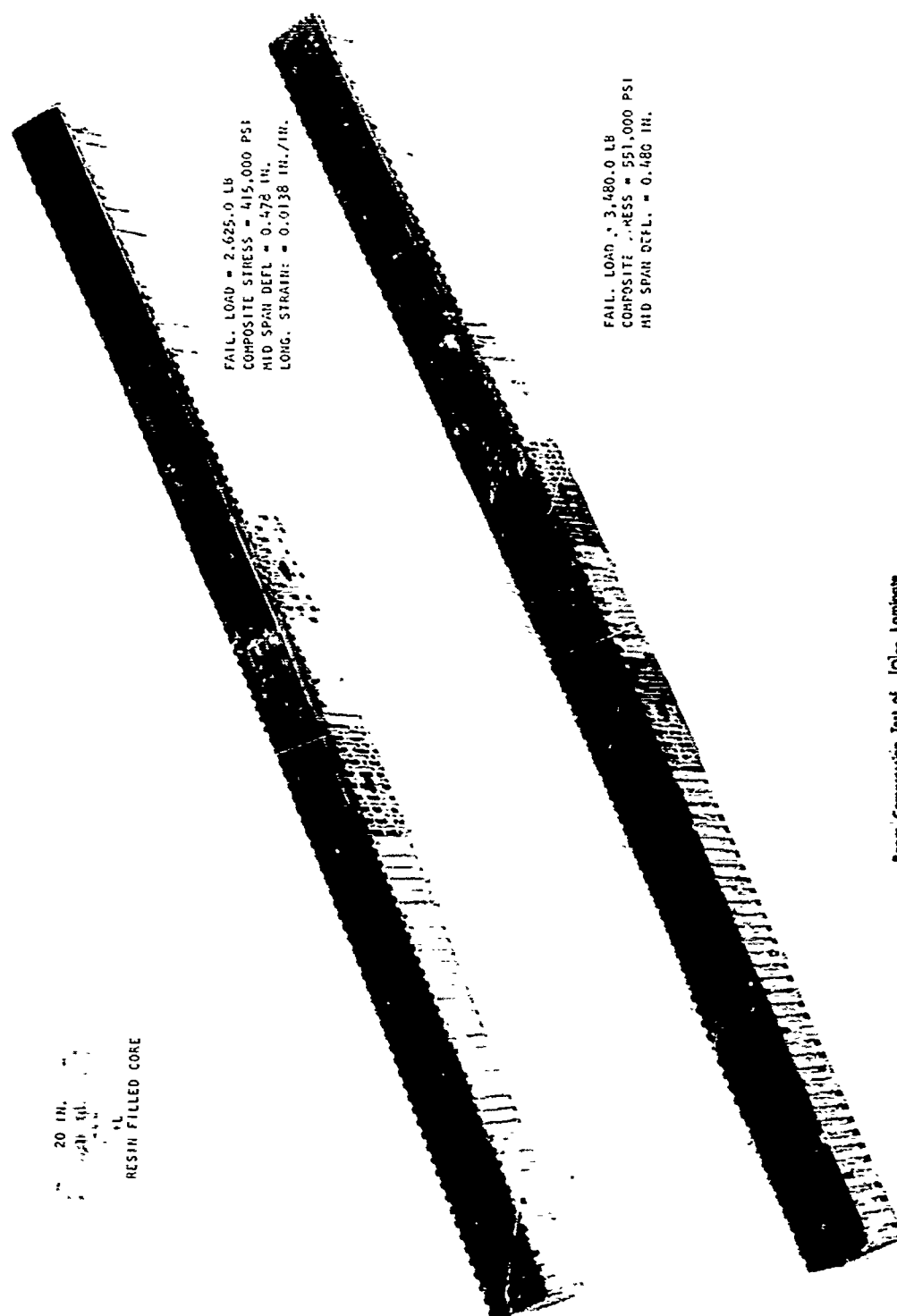
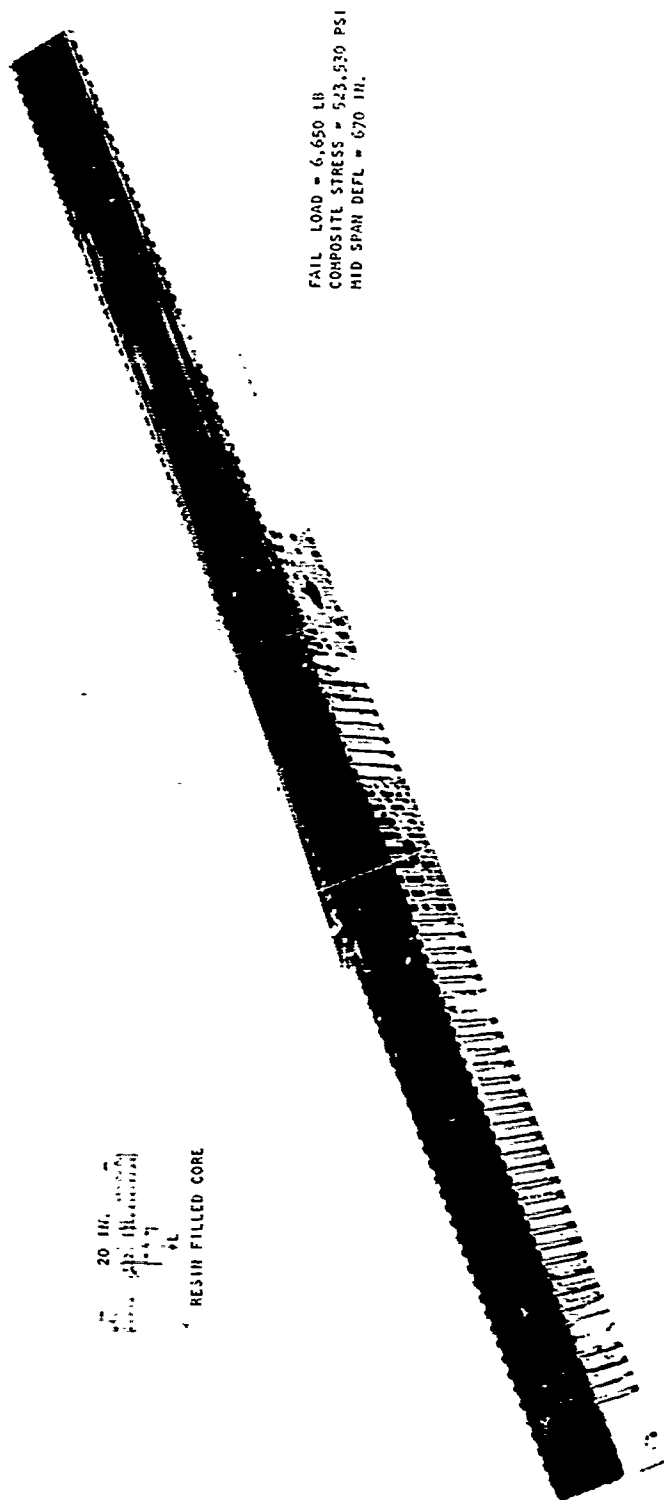


Figure 34. Beam Compression Test Specimens, [0]3T laminate



20 IN.
RESIN FILLED CORE

FAIL LOAD = 6,650 LB
COMPOSITE STRESS = 523,530 PSI
MID SPAN DEFL = 670 IN.

Beam Compression Test of [0]6T Laminate

Figure 35. Beam Compression Test Specimen [0]6T Laminate

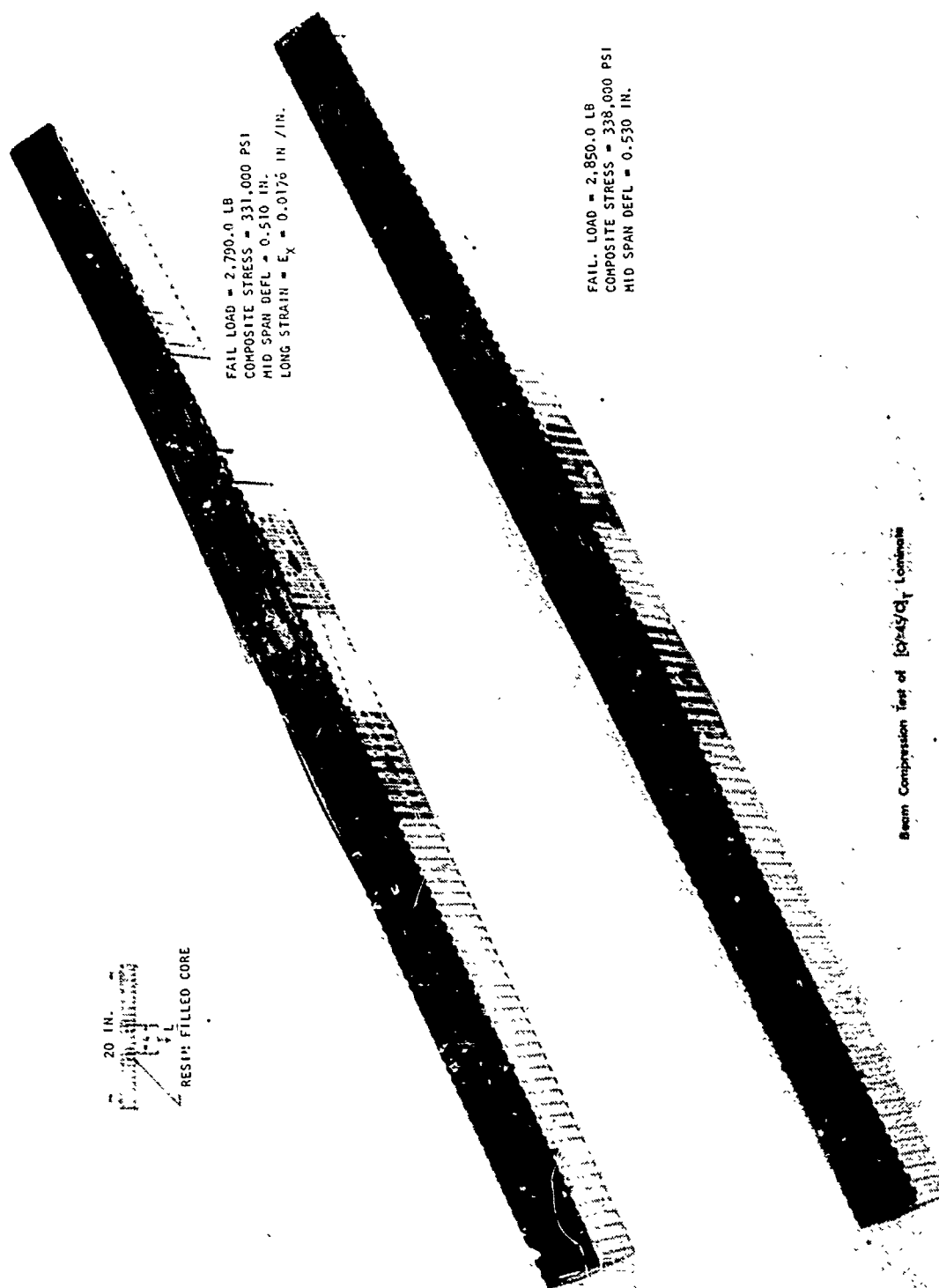
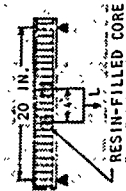


Figure 36. Beam Compression Test Specimens, $[0/+45/0]_T$ Laminate



FAIL. LOAD = 5,820.0 LB
 COMPOSITE STRESS = 343,000 PSI
 MIDSPAN DEFL = 0.68 IN.
 LONG. STRAIN: $\epsilon_x = 0.0182$ IN./IN.

FAIL. LOAD = 5,990.0 LB
 COMPOSITE STRESS = 352,600 PSI
 MIDSPAN DEFL = 0.73 IN.

Beam Compression Test of $[0/+45/0]_{2T}$ Laminate

Figure 37. Beam Compression Test Specimens, $[0/+45/0]_{2T}$ Laminate

TABLE XXXIX. FILAMENTARY LAMINATE STATIC PROPERTY DATA

Material System: Boron/Epoxy Lam Orient: [0]_{3T}
 Type Loading: Tension ☒, Comp ☐, Shear ☐, Interlam Shear ☐
 Type Test Specimen: Coupon, 1 x 9 in. with 1-1/2 in. tabs
 Soak at Temp °F for Hr. Test Temp RT °F

Property		Batch No.	288					
Spec Ident		1(1)	2(1)	3(1)			Ave.	
Stress (Ksi)	F _{p1}	5.3	5.0	5.3			5.2	
	F _{.85}	9.0	9.4	8.1			8.8	
	F _{.70}	-	-	11.0			11.0	
	F at 2/3 ϵ_1^{ult}	8.95	9.35	9.35			9.21	
	F _{ult}	11.35	11.45	11.51			11.44	
Modulus E, Gx10 ⁻⁶	E or G (primary)	2.47	2.60	2.51			2.53	
	E' or G' (secondary)	-	-	-			-	
Strain in./in.	Proportional Limit	ϵ_1	.00230	.00200	.00230			.00220
		ϵ_2	-	-	-			-
		ϵ_{45}	-	-	-			-
	Ultimate	ϵ_1	.00670	.00686	.00754			.00703
		ϵ_2	-	-	-			-
		ϵ_{45}	-	-	-			-
No. of Plies <u>3</u> Actual Laminate Thickness <u>.016*</u> Spec Laminate Thickness: Max <u>.0162</u> , Min <u>.0153</u> , Nominal <u>.0156</u> Properties based on: Nominal Thickness x ; Actual Thickness								
Filament Count <u> </u> /in. Void Content <u> </u> % Ply Thick. <u> </u> in. Fil Vol Fract <u>0.</u> Resin Wt Fract <u>0.</u> Lam Density <u> </u> lb/in. ³								
Laminate: Tape or Matrix Desig <u>5505</u> Manuf <u>Narmco</u> * Scrim Cloth Balance <u>Ply Subtracted</u> Additives Used <u> </u> Cure Spec <u>NR Spec SFC105LA0007</u>								

Comments: (1) Strain-gaged

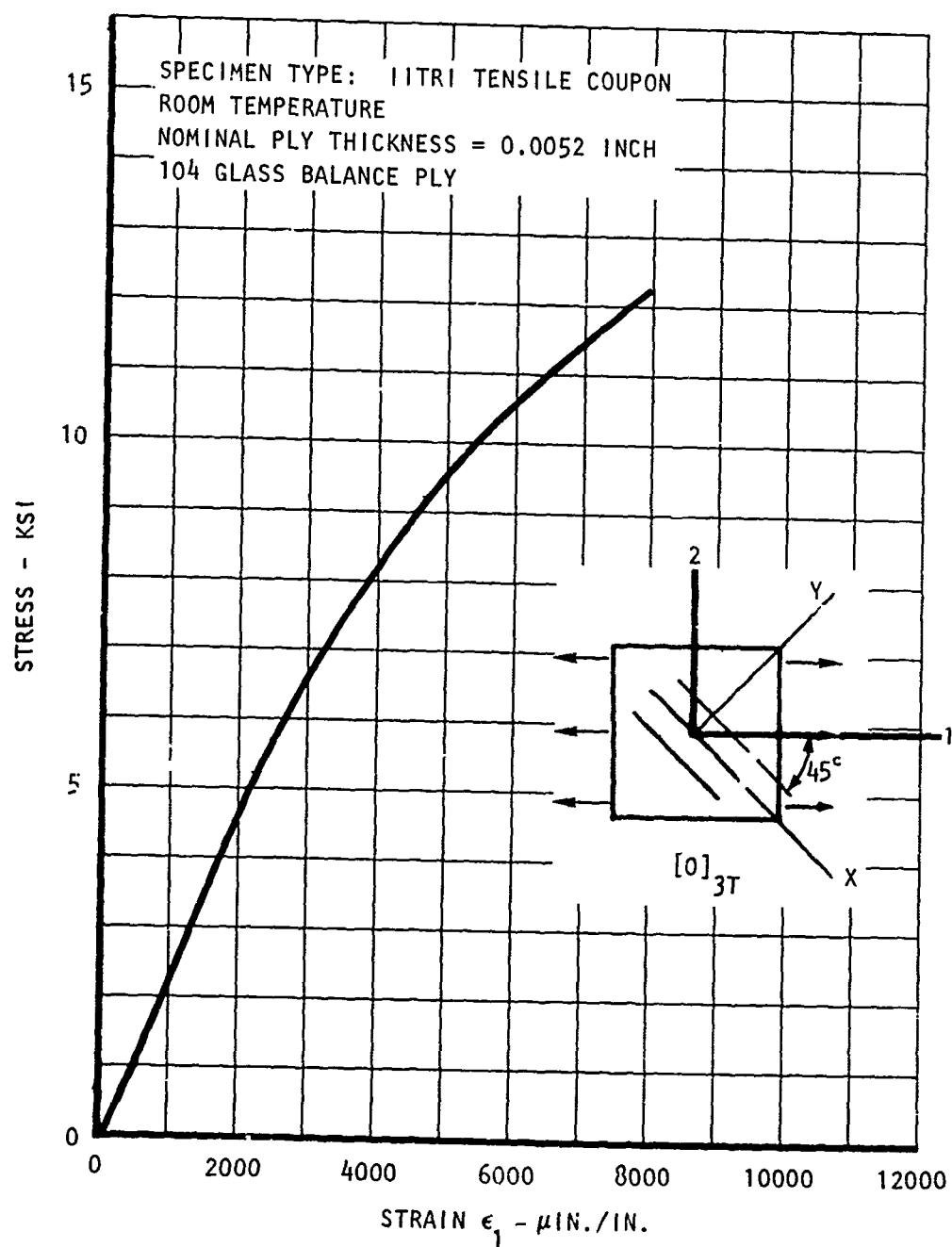


Figure 38. 45° Off-Axis Tension [0]_{3T} Laminate

TABLE XL. FILAMENTARY LAMINATE STATIC PROPERTY DATA

Material System: Boron/Epoxy Lam Orient: [0] 6T
 Type Loading: Tension ☒, Comp ☐, Shear ☐, Interlam Shear ☐
 Type Test Specimen: Coupon, 1 x 9 in. with 1-1/2 in. tabs
 Soak at Temp - °F for - Hr. Test Temp RT °F

Property		Batch No.	288					Ave.
		Spec Ident	1 (1)	2 (2)	3 (1)			
Stress (Ksi)	F _{pl}		5.1	5.1	5.1			5.1
	F _{.85}		8.60	8.85	9.20			8.88
	F _{.70}		10.35	10.6	10.90			10.63
	F at 2/3 ϵ_1^{ult}		9.90	10.80	9.90			10.20
	F _{ult}		12.40	12.89	12.37			12.55
Modulus E, Gx10 ⁻⁶	E or G (primary)		2.37	2.46	2.53			2.45
	E' or G' (secondary)		0.80	0.50	0.80			0.70
Strain in./in.	Proportional Limit	ϵ_1	.00235	.00235	.00235			.00235
		ϵ_2	-	-	-			-
		ϵ_{45}	-	-	-			-
	Ultimate	ϵ_1	.00910	.01021	.00893			.00941
		ϵ_2	-	-	-			-
		ϵ_{45}	-	-	-			-
No. of Plies <u>6</u> Actual Laminate Thickness <u>.0320 *</u> Spec Laminate Thickness: Max <u>.0324</u> , Min <u>.0306</u> , Nominal <u>.0312</u> Properties based on <u>Nominal Thickness</u> x <u>Actual Thickness</u>								
Filament Count <u> </u> /in. Void Content <u> </u> % Ply Thick. <u> </u> in. Fil Vol Fract <u>0.</u> Resin Wt Fract <u>0.</u> Lam Density <u> </u> lb/in. ³								
Laminate: Tape or Matrix Desig <u>5505</u> Manuf <u>Narmco</u> * Scrim Cloth Balance Ply Subtracted Additives Used <u> </u> Cure Spec <u>NR Spec ST0105LA0007</u>								

Comments: (1) Strain-gaged

SPECIMEN TYPE: ITTRI TENSILE COUPON
 ROOM TEMPERATURE
 NOMINAL PLY THICKNESS = 0.0052 INCH
 104 GLASS BALANCE PLY

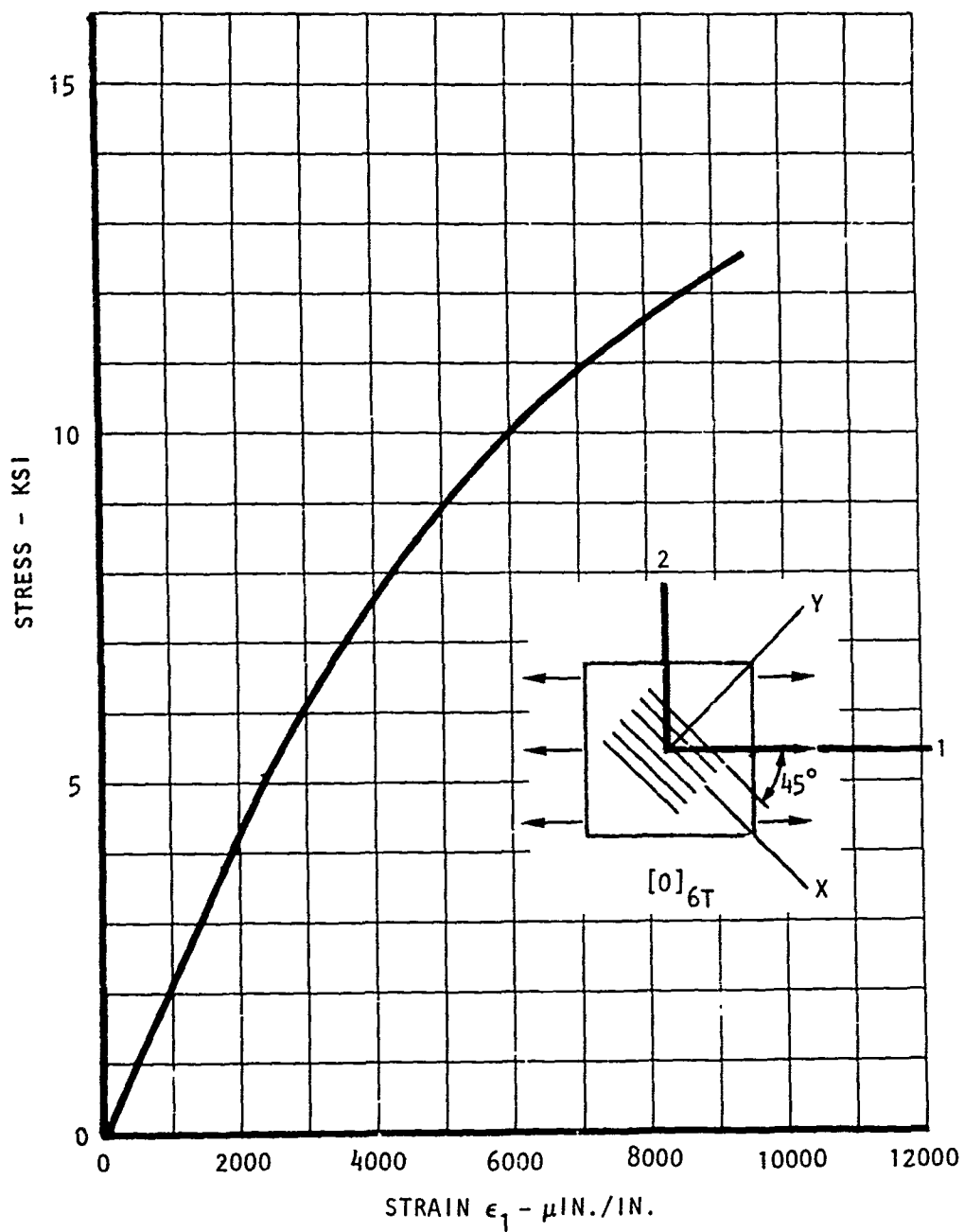
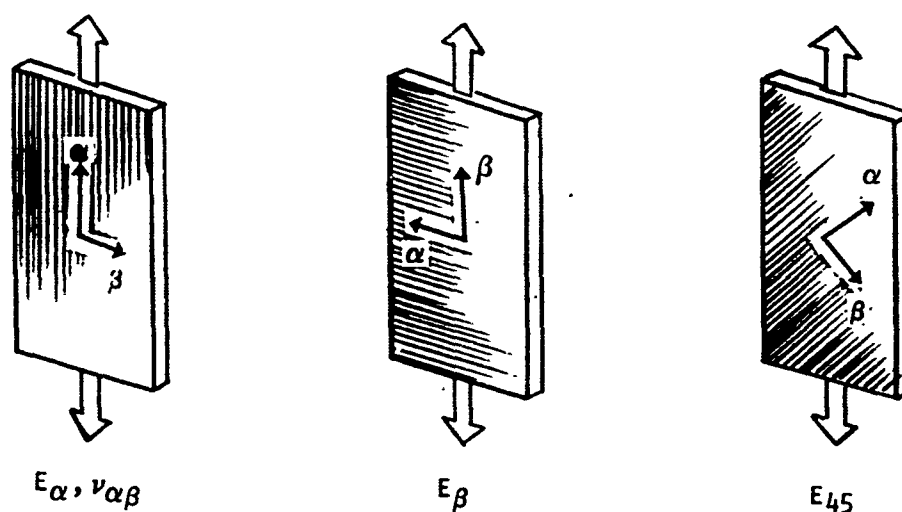


Figure 39. 45° Off-Axis Tension $[0]_{6T}$ Laminate

The shear modulus $G_{\alpha\beta}$ for unidirectional material was calculated by using the equation (reference 1):

$$G_{\alpha\beta} = \frac{1}{\frac{4}{E_{45}} - \frac{1}{E_{\alpha}} - \frac{1}{E_{\beta}} (1 - 2\nu_{\alpha\beta})}$$

where data values are defined in the following sketch:



Using the values of moduli and Poisson's ratios found in the previously tested tensile tests of the $[0]_{3T}$ and $[0]_{6T}$ laminate, and primary moduli from the 45 degree specimens, $G_{\alpha\beta}$ was calculated to be:

Laminate	$[0]_{3T}$	$[0]_{6T}$
E_{α} , Msi	30.0	30.0
E_{β} , Msi	2.64	2.71
E_{45} , Msi	2.53	2.46
$\nu_{\beta\alpha}$	0.0162	0.0175
$G_{\alpha\beta}$, Msi	0.839	0.841

FLEXURAL SPECIMEN TEST RESULTS

Because of the relatively thin laminates used in the flexural tests, the maximum moment and shear values must be corrected for the deflected shape of

the beam at failure. These values, in terms of coefficients to use with the applied load, have been developed for the three beam types, A, B, and D, shown in figure 12.

For each type of beam, values of maximum shear and maximum moment have been determined in terms of the deflection at the loading point (machine head deflection) and the thickness of the laminate. A typical deflected specimen is shown in figure 40.

The necessary correction factors are due solely to the change in geometry from deflection which changes the moment arm "a" from the reaction to the loading point, and the magnitude of the reaction due to its inclination. Since the point of contact changes because of the cylindrical surface of the support (and also the load pin for type A offcenter loading), a rather complicated relationship exists.

These factors are independent of the type of material, and assume only that the specimen is of constant thickness (moment of inertia). They deal solely with the static or free body determination of beam shear and moment loading and have nothing to do with the flexural stress distribution through the thickness of the material.

Using the shears and moments based on failing load and deflection, maximum interlaminar shear stress and outer ply bending stress have been calculated for each specimen. These stresses reflect the use of an effective flexural modulus to compensate for variation in ply moduli in the loading direction. In addition, outer ply stresses are calculated by using a "c" distance to the midpoint of the ply rather than the distance to the surface. This is because the critical point, either for filament failure or for matrix failure, will most likely occur at the midthickness of the ply.

The method of calculating the effective flexural modulus used to estimate specimen stress was based on consistent strain in the load direction but no requirement for strain consistency (uncoupled) perpendicular to the loading. This condition is representative of long, narrow specimens. Specimens which are wide relative to the length require consideration of lateral strain compatibility (coupled). On the basis of an analogy to the column versus plate transition, an aspect ratio of 1.0 was used to determine whether the uncoupled or the coupled modulus should be used. In accordance with this criterion, the coupled moduli were used only with the 0.4-inch-span specimens.

Uncoupled moduli were computed by the formula:

$$E_x^f = \frac{\sum_i (A d_{xi}^2 E_{xi}) + \sum_i (E_{xi} I_{oi})}{t^3/12}$$

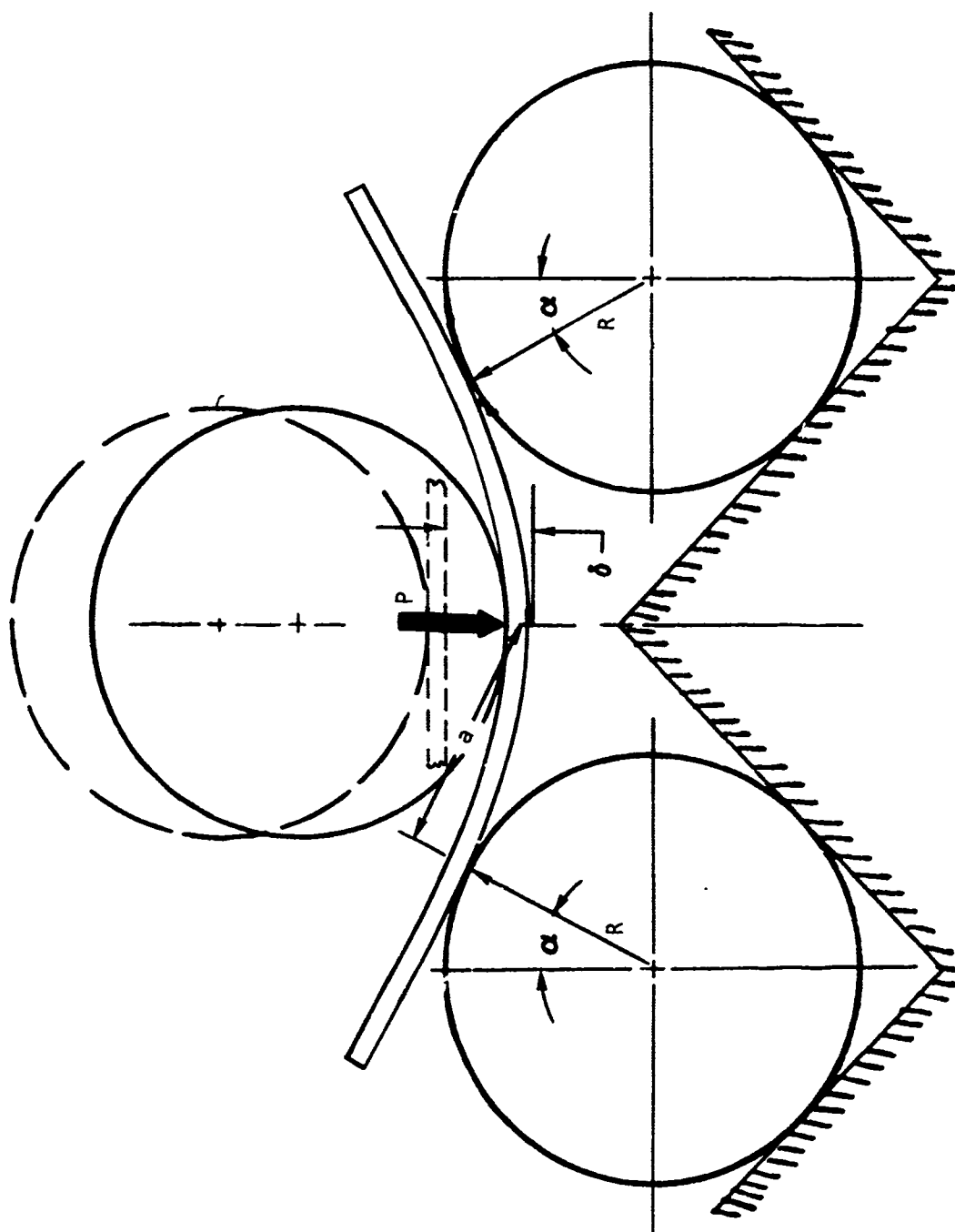


Figure 40. Typical Deflected Specimen in Flexural Test Fixture

where A, d, and E_x are the values of area, mid-ply-to-neutral-axis distance, and modulus of each of the individual plies of the laminate, and "t" is the laminate thickness. Values of EI_0 for each ply are given in table XLI.

Coupled flexural moduli were calculated from the flexural rigidity (D) values which have been developed to use in plate stability predictions.

$$E_n^{\text{flex}} = \frac{12 D_n (1 - \nu_{mn} \nu_{nm})}{t^3}$$

A summary of the extensional and flexural moduli (coupled and uncoupled) is shown in table XLI. One minor difference in approach exists, that of the model used in determining the $(EI)_0$ for a ply. These models and the resulting values are shown for the coupled and uncoupled flexural moduli.

Failing loads for the flexural specimens are presented in tables XLII through XLIV. Calculated failing interlaminar shear stress and outer ply axial stress for each specimen, based on the previously discussed approach, are shown in the same tables. Exceptionally good agreement was found in all three failure types, considering that the specimens were much thinner than the standard 15-ply flexural laminate. A summary of these results compared with typical quality control specimen data is shown in the following comparison.

Type of Test	Verification Program Laminate				Range of Batch 288 QC Data (15-ply)
	$[0]_{3T}$	$[0]_{6T}$	$[0/\pm 45/0]_T$	$[0/\pm 45/0]_{2T}$	
Interlaminar shear, ksi	16.0	20.1	11.8	14.8	13.5 to 16.1
Longitudinal flexure, ksi	218	196	192	194	227 to 253
Transverse flexure, ksi	13.5	13.4	24.0	16.2	15.0 to 17.0

Interlaminar Shear

Table XLII presents results of the interlaminar shear (type A) specimens. Comparison of the interlaminar shear and the flexural stresses indicates that all specimens failed in the interlaminar-shear-critical mode. Interlaminar shear failing stresses of the $[0/\pm 45/0]_C$ four-ply and eight-ply laminates were 11.8 and 14.8 ksi, respectively, and close to the predicted 13.0 ksi strength. Values for the $[0]_C$ three-ply and six-ply specimens were 16.0 and 20.1 ksi,

TABLE XLI. EXTENSIONAL AND FLEXURAL MODULI VALUES

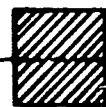


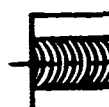
Orientation	Property	E Extensional Msi	E ^{flex} Coupled (Wide Plate) Msi	E ^{flex} Uncoupled (Beam) Msi	
[0] _{3T}	E _x	31.25	31.25	29.30	
	E _y	3.55	3.55	3.25	
[0] _{6T}	E _x	31.25	31.25	30.8	
	E _y	3.55	3.55	3.49	
[0/±45/0] _T	E _x	17.7	24.4	27.2	
	E _y	5.91	3.76	3.33	
[0/±45/0] _{2T}	E _x	17.7	19.4	19.7	
[0/±45/0] _S	E _y	5.91	5.37	3.32	
<p>*Properties t = 0.0052 in. Fil/in. = 212 E_t = 60 Msi E_m = 0.50 Msi</p> <p>**Properties t = 0.0052 in. E_x = 31.25 Msi uniform E_y = 3.55 Msi uniform (EI)_o^H = single ply value assuming material is homogeneous. (EI)_o^R = single ply value assuming material consists of filament and a matrix with their individual moduli considered in the analysis.</p>		Model for Single-Ply Local Inertia	Longitudinal Ply (EI) _{ox}	<p>* </p> <p>(E_xI)_o^H = 0.366 $\frac{\text{lb-in.}^2}{\text{in.}}$</p>	<p>** </p> <p>(E_xI)_o^R = 0.165 $\frac{\text{lb-in.}^2}{\text{in.}}$</p>
			Transverse Ply (EI) _{oy}	<p></p> <p>(E_yI)_o^H = 0.0145 $\frac{\text{lb-in.}^2}{\text{in.}}$</p>	<p></p> <p>(E_yI)_o^R = 0.0102 $\frac{\text{lb-in.}^2}{\text{in.}}$</p>

TABLE XLII. INTERLAMINAR SHEAR-CRITICAL FLEXURAL SPECIMEN FAILING STRESSES

Laminate Orientation Specimen Type	No. of Plies	Specimen			Proportional Limit		Failing		Maximum* Shear (lb)	Maximum* Moment (in.)	Maximum** Interlaminar Shear Stress (avg) Ksi	Maximum** Flexure Stress (avg) Ksi
		No.	Width (in.)	Thick (in.)	Load (lb)	Defl (in.)	Load (lb)	Defl (in.)				
[0] _{3T} Type A	3	1	0.25	0.0165	43.9	0.0170	46.9	0.0190	45.72	1.050	16.0	69.5
		2	0.25	0.0164	48.3	0.0180	49.3	0.0195	49.30	0.872		
		3	0.25	0.0163	44.8	0.0173	46.5	0.0184	43.94	1.418		
		4	0.25	0.0164	45.8	0.0169	48.9	0.0195	48.90	0.865		
[0] _{6T} Type A	6	1	0.25	0.0328	100.0	0.0112	116.0	0.0150	102.0	4.616	20.1	80.1
		2	0.25	0.0330	92.0	0.0106	117.0	0.0153	104.1	4.504		
		3	0.25	0.0329	98.0	0.0122	115.0	0.0160	104.0	4.025		
		-	-	-	-	-	-	-	-	-		
[0/±45/0] _T Type A	4	2	0.25	0.0218	-	-	46.3	0.0149	41.67	2.004	11.8	109.5
		3	0.25	0.0217	-	-	46.3	0.0149	41.67	2.004		
		4	0.25	0.0216	-	-	46.5	0.0145	41.47	2.092		
		5	0.25	0.0219	-	-	46.0	0.0142	40.84	2.116		
[0/±45/0] _{2T} Type A	8	1	0.25	0.0427	122.0	0.0120	128.0	0.0130	112.6	5.824	14.8	112.4
		2	0.25	0.0425	121.0	0.0120	129.0	0.0135	115.2	5.598		
		3	0.25	0.0424	117.0	0.0111	132.8	0.0135	118.5	5.763		
		4	0.25	0.0422	118.0	0.0110	131.8	0.0134	117.1	5.799		

* Considering deflection effects on reaction and span

** Considering the directional moduli of the plies and bending stress at midplane of the surface ply

respectively. The lowest value, 11.8 ksi, occurred between +45° and -45° oriented plies. All other values occurred between 0° plies.

Longitudinal Flexure

Table XLIII presents results from the longitudinal flexural test specimens. The $[0]_{3T}$ specimen was first tested as a type D (2-inch span) beam but could not be failed because of excessive deflection. It was then loaded as a type B beam to failure. All other laminates were failed as type D beams.

The $[0]_{3T}$ type B specimen gave a somewhat higher value of flexural stress (218 ksi) than the other three orientations, which were very consistent (196, 192, and 194 ksi). These values are in good agreement with the higher values from carefully conducted tension coupon tests.

Transverse Flexure

Table XLIV presents results from the transverse flexural test specimens. Two types of specimen configuration are represented. The $[0]_{3T}$ three-ply and the $[0/\pm 45/0]_T$ four-ply specimens were tested in the 0.4-span, type B beam configuration. The thicker $[0]_{6T}$ and $[0/\pm 45/0]_{2T}$ specimens were tested using the 2-inch span, type D beam.

Transverse failing stresses of the $[0]_C$ laminates were consistent (13.5 and 13.5 ksi) and agree well with the 13.0 ksi allowable. This is in spite of the difference in laminate thickness and specimen types.

Transverse stresses of the four-ply and eight-ply $[0/\pm 45/0]_C$ laminates were 24.0 and 16.2 ksi, respectively, which exceed the estimated allowable. This may result from some yielding in the outer (transverse) ply and its support by the stiffer 45-degree-oriented adjacent ply.

TRANSVERSE PROPERTY IMPROVEMENT STUDY

A study was initiated to develop improved transverse properties for unidirectional laminates, a goal which was felt would be highly beneficial to unidirectional composite applications in this program, such as hat- and Z-section stiffeners. NR/LAD conceived the idea of rotating the scrim cloth 90 degrees relative to its normal direction to orient the stronger (warp) axis of the cloth in the transverse direction of the unidirectional prepreg tape.

One roll (No. 8 - 248 feet) of Narmco batch 334 (special) was special-ordered, with the 104 glass scrim rotated 90 degrees. The 104 glass has a breaking strength of 55 lb/in. in the warp direction and 20 lb/in. in the

TABLE XLIII. LONGITUDINAL FLEXURAL SPECIMEN FAILING STRESSES

Laminate Orientation Specimen Type	No. of Plies	Specimen			Proportional Limit		Failing		Maximum [†] Shear (lb)	Maximum [*] Moment (in.-lb)	Maximum ^{**} Interlaminar Shear Stress (avg) Ksi	Maximum ^{**} Flexure Stress (avg) Ksi
		No.	Width (in.)	Thick (in.)	Load (lb)	Defl (in.)	Load (lb)	Defl (in.)				
[0] _{3T} Type B	3	1	0.50	0.0168			74.0	0.0264	38.06	6.660	6.4	218
		2	0.50	0.0171			75.3	0.0268	38.75	6.762		
		3	0.50	0.0170			71.8	0.0256	36.82	6.498		
[0] _{6T} Type D	6	1	0.50	0.0332	76.8	0.1537	90.3	0.1968	85.15	37.29	8.4	196
		2	0.50	0.0330	72.8	0.1445	95.5	0.2067	91.89	40.11		
		3	0.50	0.0331	87.0	0.1754	91.5	0.1900	85.46	37.51		
[0/±45/0] _{4T} Type D	4	1	0.50	0.0221	22.1	0.1670	29.6	0.3083	37.56	15.98	4.8	192
		2	0.50	0.0223	23.0	0.1700	30.6	0.2815	35.37	15.15		
		3	0.50	0.0222	24.4	0.1910	31.5	0.3110	40.22	17.11		
[0/±45/0] _{8T} Type D	8	1	0.50	0.0432			95.0	0.1262	85.88	38.95	5.4	194
		2	0.50	0.0437			101.0	0.1315	92.13	41.21		
		3	0.50	0.0435			98.0	0.1310	89.55	40.08		

* Considering deflection effects on reaction and span

** Considering the directional moduli of the plies and bending stress at midplane of the surface ply

TABLE XLIV. TRANSVERSE FLEXURAL SPECIMEN FAILING STRESSES

Laminate Orientation Specimen Type	No. of Plies	Specimen			Proportional Limit		Failing		Maximum* Shear (lb)	Maximum* Moment (in.-lb)	Maximum** Interlaminar Shear Stress (avg) Ksi	Maximum** Flexure Stress (avg) Ksi
		No.	Width (in.)	Thick (in.)	Load (lb)	Defl (in.)	Load (lb)	Defl (in.)				
[0] _{3T} Type B	3	1	0.50	0.0165	2.8	0.0095	4.2	0.0150	2.128	0.399	0.48	13.5
		2	0.50	0.0166	4.3	0.0148	4.5	0.0160	2.285	0.425		
		3	0.50	0.0164	1.5	0.0071	4.3	0.0145	2.180	0.408 avg		
[0] _{6T} Type D	6	1	0.50	0.0328	5.2	0.1200	6.3	0.1685	5.777	2.55	0.57	13.4
		2	0.50	0.0327	5.5	0.1262	6.6	0.1782	6.104	2.69		
		3	0.50	0.0322	4.0	0.0940	6.4	0.1785	5.935	2.61 avg		
[0/±45/0] _T Type B	4	1	0.50	0.0223	9.4	0.0180	24.5	0.0545	17.57	1.34	1.57	24.0
		2	0.50	0.0223	8.3	0.0150	18.6	0.0500	11.51	1.36		
		3	0.50	0.0221	6.5	0.0135	24.2	0.0555	15.61	0.968 avg		
[0/±45/0] _{2T} Type D	8	1	0.50	0.0413	7.8	0.0519	16.3	0.1187	14.85	6.67	1.12	16.2
		2	0.50	0.0422	13.5	0.0850	17.8	0.1235	16.23	7.28		
		3	0.50	0.0419	10.4	0.0685	17.0	0.1175	15.49	6.97 avg		

* Considering deflection effects on reaction and span

** Considering the directional moduli of the plies and bending stress at midplane of the surface ply

fill direction. A 15-ply unidirectional laminate was fabricated from this special batch, and data from this laminate were compared with the average of NR data from batch 334, rolls 1, 10, and 14 (standard scrim orientation) in table XLV.

TABLE XLV. COMPARISON OF ROTATED SCRIM AND STANDARD LAMINATE PROPERTIES

	Average Three Rolls Standard Scrim Orientation	Scrim Rotated 90°
Longitudinal flexure, RT	245 ksi	246 ksi
Longitudinal flexure, 350°F	200	196
Transverse flexure, RT	14.6	19.3
Transverse flexure, 350°F	10.9	18.7
Interlaminar shear, RT	15.0	14.7
Interlaminar shear, 350°F	6.6	7.4

From this table, it is seen that the transverse flexure strength shows a remarkable increase from rotating the orthotropic scrim cloth, amounting to a 32 percent increase at room temperature and a 72 percent increase at 350°F. The longitudinal flexure and interlaminar shear results are within the scatter range for normal material. Thus, on the basis of these data, it would appear that by rotating the scrim cloth 90 degrees, the transverse strength of a ply is greatly increased, while the other strength properties remain virtually unchanged.

In addition to the quality control data, longitudinal and transverse tension unidirectional IITRI-type coupon specimens were tested at room temperature and 350°F. The numerical results of these tests are given in tables XLVI through XLIX. Average stress-strain curves are also presented in figures 43 and 44, on which are plotted rotated and nonrotated results to provide a comparison of the two types of data.

Figure 41 indicates that the test values for the longitudinal room temperature Young's modulus and ultimate strength of the rotated scrim specimen are slightly lower than the nonrotated specimen, but this difference is suspect in view of the data shown in table XLV. The 350° F results for the same type of test, as shown in figure 42, indicate that there is virtually no difference between the rotated and nonrotated results. This is as expected, since the boron filaments essentially determine the longitudinal strength of the unidirectional boron/epoxy laminate.

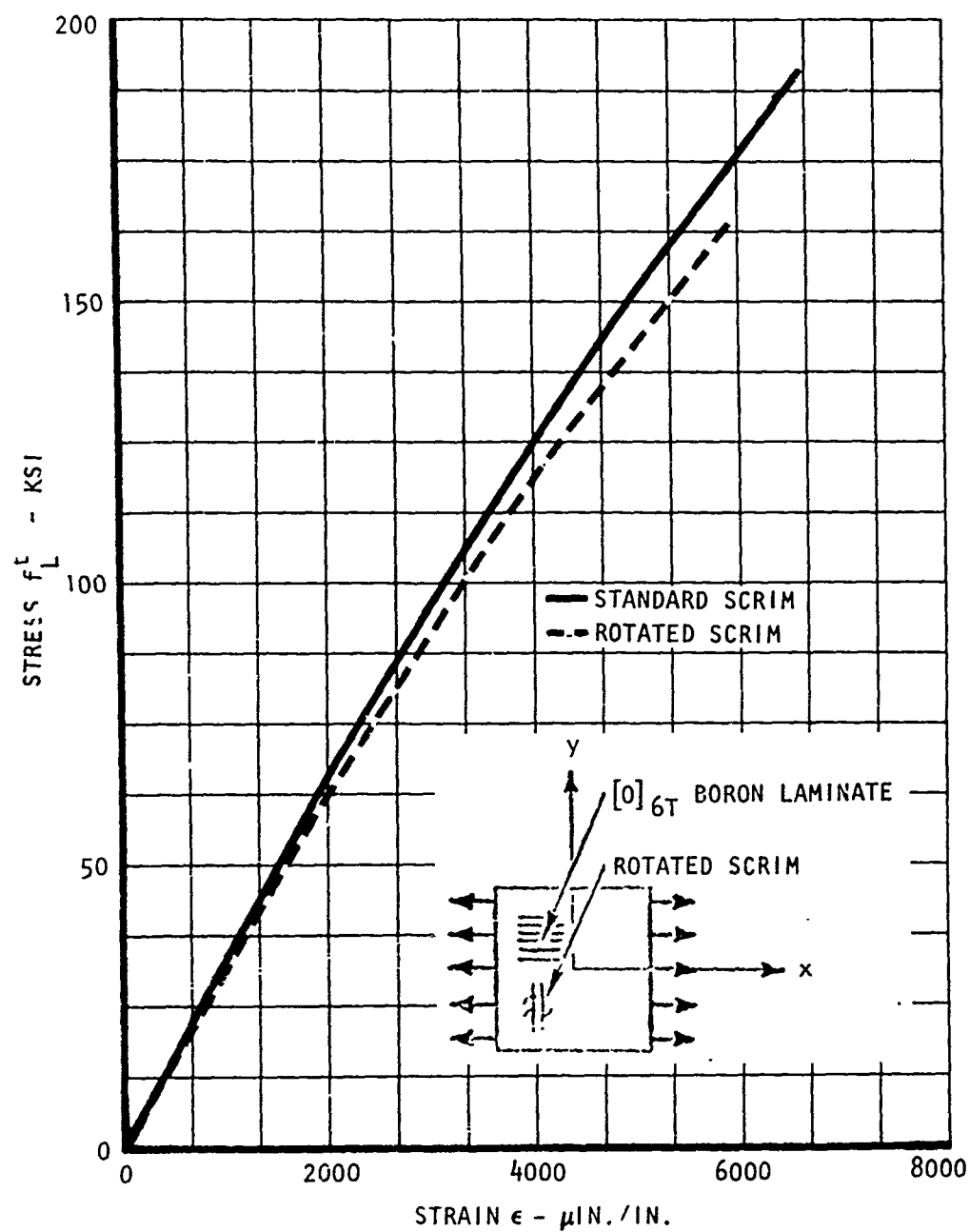


Figure 41. Rotated Scrim Longitudinal Tension Stress-Strain Curve Comparison with Non-Rotated Data for Narmco 5505 at Room Temperature

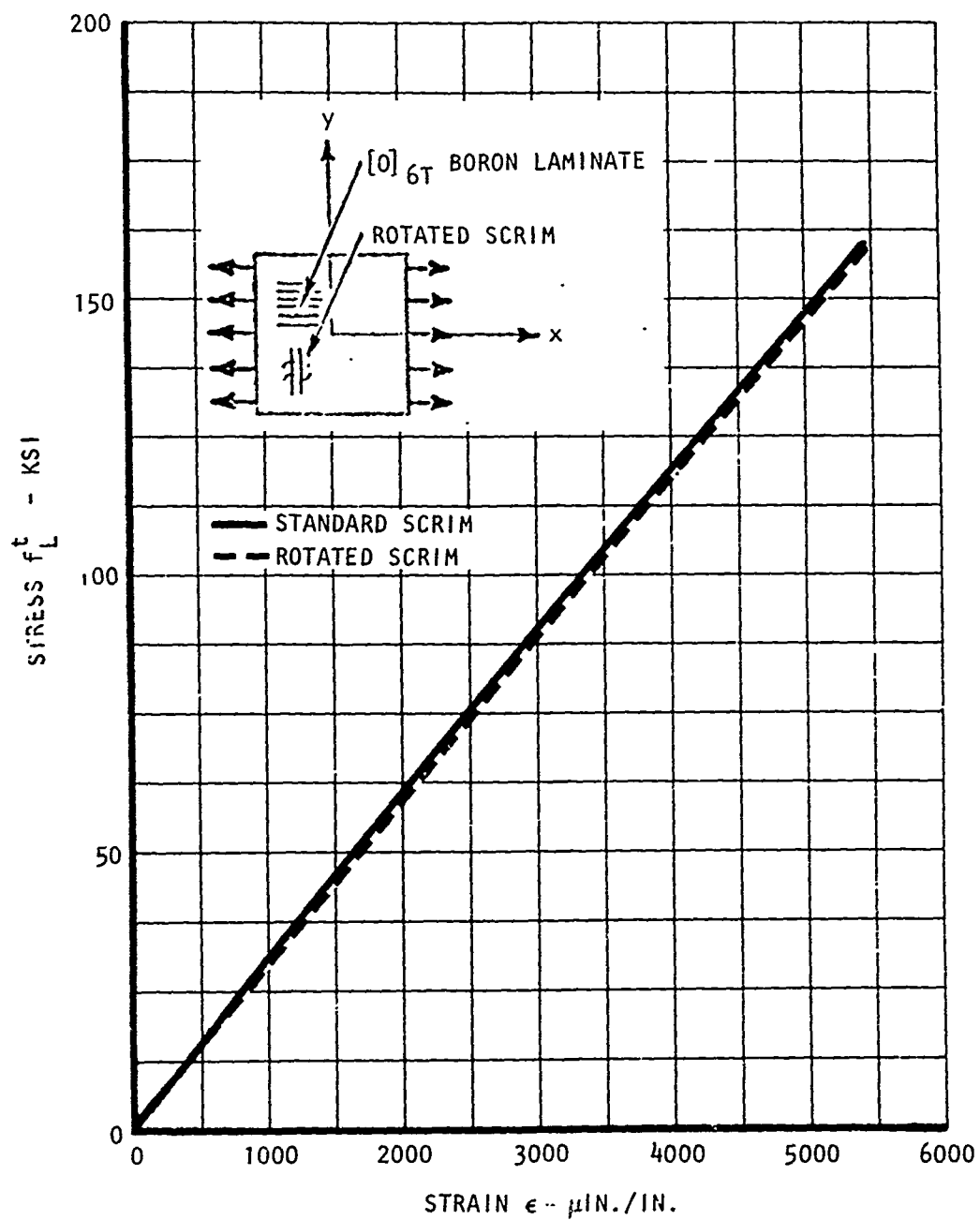


Figure 42. Rotated Scrim Longitudinal Tension Stress-Strain Curve Comparison With Non-Rotated Data for Narmco 5505 at 350°F

TABLE XLVI. FILAMENTARY LAMINATE STATIC PROPERTY DATA

Material System: Boron/Epoxy (Rotated Scrim) Lam Orient: [0]_{6T}
 Type Loading: Tension ☒, Comp ☐, Shear ☐, Interlam Shear ☐
 Type Test Specimen: Coupon, 1/2 x 9 in. with 1-1/2 in. tabs Load Orient: 0°
 Soak at Temp °F for Hr. Test Temp RT °F

Property		Batch No. 334	Spec Ident	2-1(2)	2-2(2)	2-3(2)	2-6(2)	Ave.
Stress (Ksi)	F_{pl}			34.0	50.0	42.0	34.0	40.0
	$F_{.85}$							
	$F_{.70}$							
	F at $2/3 \epsilon_1^{ult}$							
	F_{ult}			169	165	156	166	164
Modulus $E, G \times 10^{-6}$	E or G (primary)			28.8	28.6	28.0	28.8	28.5
	E' or G' (secondary)							
Strain in./in.	Proportional Limit	ϵ_1		.00120	.00170	.00150	.00120	.00140
		ϵ_2		-	-	.00225	.000225	.000225
		ϵ_{45}						
	Ultimate	ϵ_1		.00610	.00595	.00565	.00590	.00590
		ϵ_2				.00105	.00118	.00111
		ϵ_{45}						
No. of Plies <u>6</u> Actual Laminate Thickness <u>(1)</u> Spec Laminate Thickness: Max <u> </u> , Min <u> </u> , Nominal <u>.0312</u> Properties based on: Nominal Thickness X ; Actual Thickness								
Filament Count <u> </u> /in. Void Content <u> </u> % Ply Thick. <u> </u> in. Fil Vol Fract <u>0.</u> Resin Wt Fract <u>0.</u> Lam Density <u> </u> lb/in. ³								
Laminate: Tape or Matrix Desig <u>Rotated Scrim 5505</u> Manuf <u>Narmco</u> Scrim Cloth <u>104 Glass Fabric</u> Warp Additives Used <u>None</u> Cure Spec <u>NR Spec ST0105LA0007</u> at <u>90°</u>								

Comments: (1) After subtracting 0.001 in. for scrim balance ply
 (2) Deformation data from strain gages

TABLE XLVII. FILAMENTARY LAMINATE STATIC PROPERTY DATA

Material System: Boron/Epoxy (Rotated Scrim) Lam Orient: [0]_{6T}
 Type Loading: Tension ☒, Comp ☐, Shear ☐, Interlam Shear ☐
 Type Test Specimen: _____ Load Orient: 0°
 Soak at Temp _____ °F for _____ Hr. Test Temp 350 °F

Property		Batch No. _____ Spec Ident _____						Ave.
Stress (Ksi)	F _{P1}		62.5					'62.5
	F _{.85}							
	F _{.70}							
	F at 2/3 ϵ_1^{ult}							
	F _{ult}		161					161
Modulus E, Gx10 ⁻⁶	E or G (primary)		29.7					29.7
	E' or G' (secondary)							
Strain in./in.	Proportional Limit	ϵ_1	.00210					.00210
		ϵ_2						
		ϵ_{45}						
	Ultimate	ϵ_1	.00530					.00530
		ϵ_2						
		ϵ_{45}						
No. of Plies _____ Actual Laminate Thickness <u>(1)</u> Spec Laminate Thickness: Max _____, Min _____, Nominal <u>.0312</u> Properties based on: Nominal Thickness X ; Actual Thickness _____								
Filament Count _____ /in. Void Content _____ % Ply Thick. _____ in. Fil Vol Fract <u>0.</u> Resin Wt Fract <u>0.</u> Lam Density _____ lb/in. ³								
Laminate: Tape or Matrix Desig <u>Rotated Scrim 5505</u> Manuf <u>Narmco</u> Scrim Cloth <u>104 Glass Fabric-Warp</u> Additives Used <u>None</u> Cure Spec <u>NR Spec ST0105LA0007</u> at <u>90°</u>								

Comments: (1) After subtracting 0.001 in. for scrim balance ply

TABLE XLVIII. FILAMENTARY LAMINATE STATIC PROPERTY DATA

Material System: Boron/Epoxy (Rotated Scrim) Lam Orient: [0]_{6T}
 Type Loading: Tension ☒, Comp ☐, Shear ☐, Interlam Shear ☐
 Type Test Specimen: Coupon, W(1) x 9 in. with 1-1/2 in. tabs Load Orient: 90°
 Soak at Temp - °F for - Hr. Test Temp RT °F

Property		Batch No.						
		Spec Ident	1	2	3	4	5	
Stress (Ksi)	F _{pl}		6.92	7.31	6.20	7.23	6.39	
	F _{.85}							
	F _{.70}							
	F at 2/3 ϵ_1^{ult}							
	F _{ult}		10.32	10.39	10.59	9.78	9.48	
Modulus E, G x 10 ⁵	E or G (primary)		2.84	2.90	3.65	3.19	3.17	
	E' or G' (secondary)							
Strain in./in.	Proportional Limit	ϵ_1	.00224	.00252	.00170	.00238	.00279	
		ϵ_2						
		ϵ_{45}						
	Ultimate	ϵ_1	.00390	.00414	.00360	.00371	.00396	
		ϵ_2						
		ϵ_{45}						
No. of Plies _____ Actual Laminate Thickness <u>(2)</u> Spec Laminate Thickness: Max _____, Min _____, Nominal <u>.0312</u> Properties based on: Nominal Thickness X ; Actual Thickness _____								
Filament Count _____ /in. Void Content _____ % Ply Thick. _____ in. Fil Vol Fract <u>0.</u> Resin Wt Fract <u>0.</u> Lam Density _____ lb/in. ³								
Laminate: Tape or Matrix Desig <u>Rotated Scrim 5505</u> Manuf <u>Narmco</u> Scrim Cloth <u>104 Glass Fabric</u> Additives Used <u>None</u> Cure Spec <u>NR Spec ST0105LA0007</u>								

Comments: (1) W = 1 in. for specimens 1, 2, and 3; 1/2 in. for specimens 4, 5, 6, and 7
 (2) After subtracting 0.001 for scrim balance ply

TABLE XLVIII. FILAMENTARY LAMINATE STATIC PROPERTY DATA (CONCLUDED)

Material System: Boron/Epoxy (Rotated Scrim) Lam Orient: [0]_{6T}
 Type Loading: Tension ☒, Comp ☐, Shear ☐, Interlam Shear ☐
 Type Test Specimen: Coupon, W(1) x 9 in. with 1-1/2 in. tabs Load Orient: 90°
 Soak at Temp °F for Hr. Test Temp RT °F

Property		Batch No.						
		Spec Ident	6	7				Ave.
Stress (Ksi)	F _{p1}		6.39	6.29				6.70
	F _{.85}							
	F _{.70}							
	F at 2/3 ϵ_1^{ult}							
	F _{ult}		9.48	9.43				9.97
Modulus E, G x 10 ⁻⁶	E or G (primary)		3.64	2.80				5.17
	E' or G' (secondary)							
Strain in./in.	Proportional Limit	ϵ_1	.00236	.00220				.00251
		ϵ_2						
		ϵ_{45}						
	Ultimate	ϵ_1	.00363	.00338				.00376
		ϵ_2						
		ϵ_{45}						
No. of Plies <u>6</u> Actual Laminate Thickness <u> </u> Spec Laminate Thickness: Max <u> </u> , Min <u> </u> , Nominal <u>.0312</u> Properties based on: Nominal Thickness <u>X</u> ; Actual Thickness <u> </u>								
Filament Count <u> </u> /in. Void Content <u> </u> % Ply Thick. <u> </u> in. Fil Vol Fract <u>0.</u> Resin Wt Fract <u>0.</u> Lam Density <u> </u> lb/in. ³								
Laminate: Tape or Matrix Desig <u>Rotated Scrim 5505</u> Manuf <u>Narmco</u> Scrim Cloth <u>104 Glass Fabric</u> Additives Used <u>None</u> Cure Spec <u>NR Spec ST0105LA0007</u>								

Comments: (1), (2) See previous page

TABLE XLIX. FILAMENTARY LAMINATE STATIC PROPERTY DATA

Material System: Boron/Epoxy (Rotated Scrim) Lam Orient: [0]_{6r}
 Type Loading: Tension ☒, Comp ☐, Shear ☐, Interlam Shear ☐
 Type Test Specimen: Coupon, 1 x 9 in. with 1-1/2 in. tabs Load Orient: 90°
 Soak at Temp _____ °F for _____ Hr. Test Temp 350 °F

Property		Batch No.	Spec Ident	1-4	E1	E2	E3		Ave.
Stress (Ksi)	F _{P1}			4.42	4.08	3.85	3.87		4.06
	F _{.85}								
	F _{.70}								
	F at 2/3 ϵ_1^{ult}								
	F _{ult}			7.81	6.48	6.71	6.40		6.85
Modulus 10 ⁶ x 10 ⁻⁶	E or G (primary)			1.60	1.60	1.51	1.76		1.62
	E' or G' (secondary)								
Strain in./in.	Proportional Limit	ϵ_1		.00230	.00255	.00255	.00219		.00257
		ϵ_2							
		ϵ_{45}							
	Ultimate	ϵ_1		.00488	.00453	.00459	.00420		.00455
		ϵ_2							
		ϵ_{45}							
No. of Plies <u>6</u> Actual Laminate Thickness _____ Spec Laminate Thickness: Max _____, Min _____, Nominal <u>.0512</u> Properties based on: Nominal Thickness \ ; Actual Thickness									
Filament Count _____ /in. Void Content _____ % Ply Thick. _____ in. Fil Vol Fract <u>0.</u> Resin Wt Fract <u>0.</u> Lam Density _____ lb/in. ³									
Laminate: Tape or Matrix Desig <u>Rotated Scrim 5505</u> Manuf <u>Narmco</u> Scrim Cloth <u>104 Glass Fabric</u> Additives Used <u>None</u> Cure Spec <u>NR Spec ST0105LA0007</u>									

Comments: _____

The transversely loaded rotated scrim specimens show definite improvements in stiffness as well as strength over standard scrim results, as shown in figures 43 and 44. The increase in properties is especially evident in the 350°F data. This is evidently due to the fact that the scrim cloth is less affected by the high temperature than the resin; thus, in the 350°F environment, the scrim cloth properties decrease in a smaller proportion than the resin properties. This same reasoning would explain the 72 percent increase in rotated scrim transverse flexure quality control data over standard scrim data, as mentioned earlier for the 350°F environment, while only a 31 percent increase was encountered at room temperature.

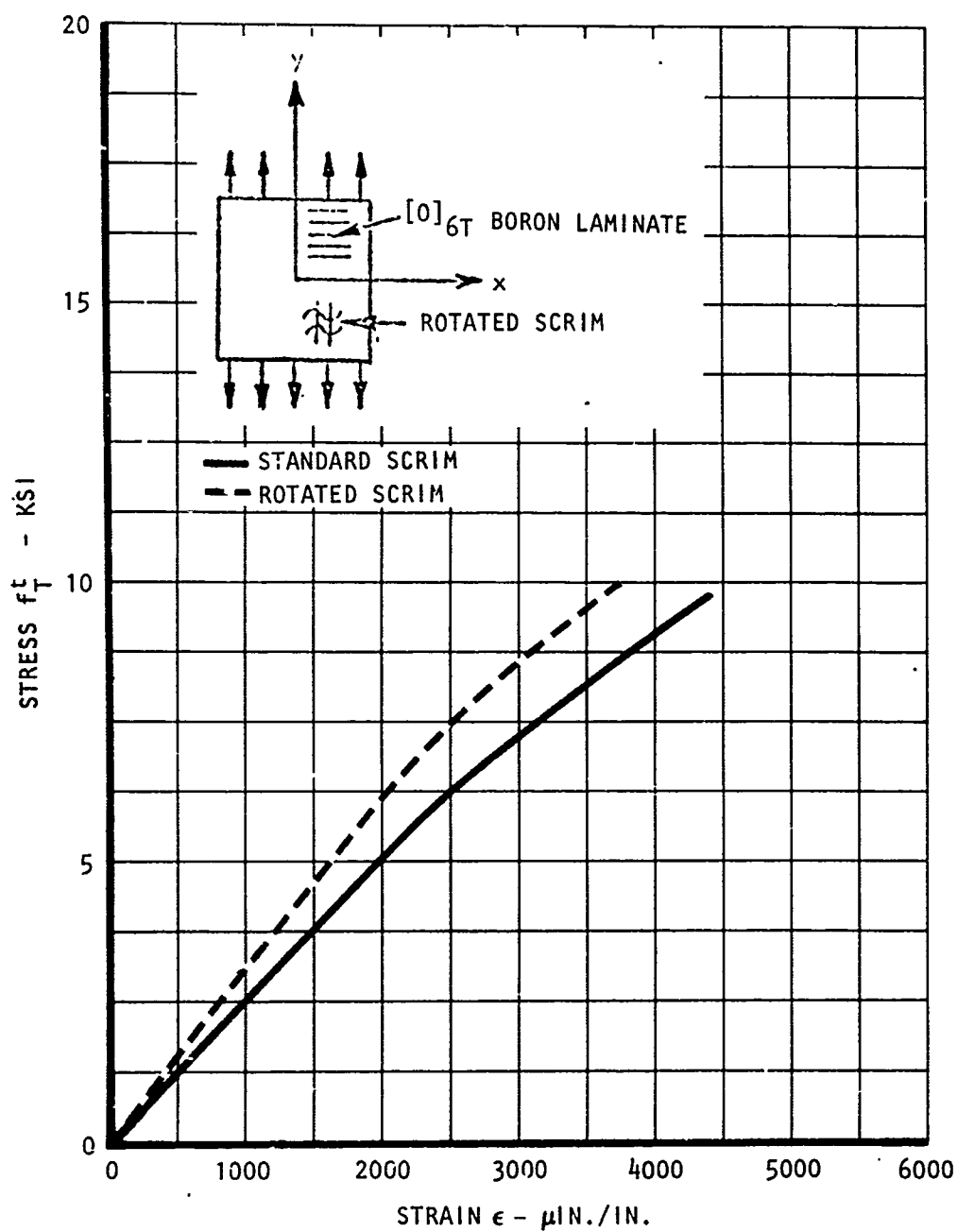


Figure 43. Rotated Scrim Transverse Tension Stress-Strain Curve Comparison With Non-Rotated Data for Narmco 5505 at Room Temperature

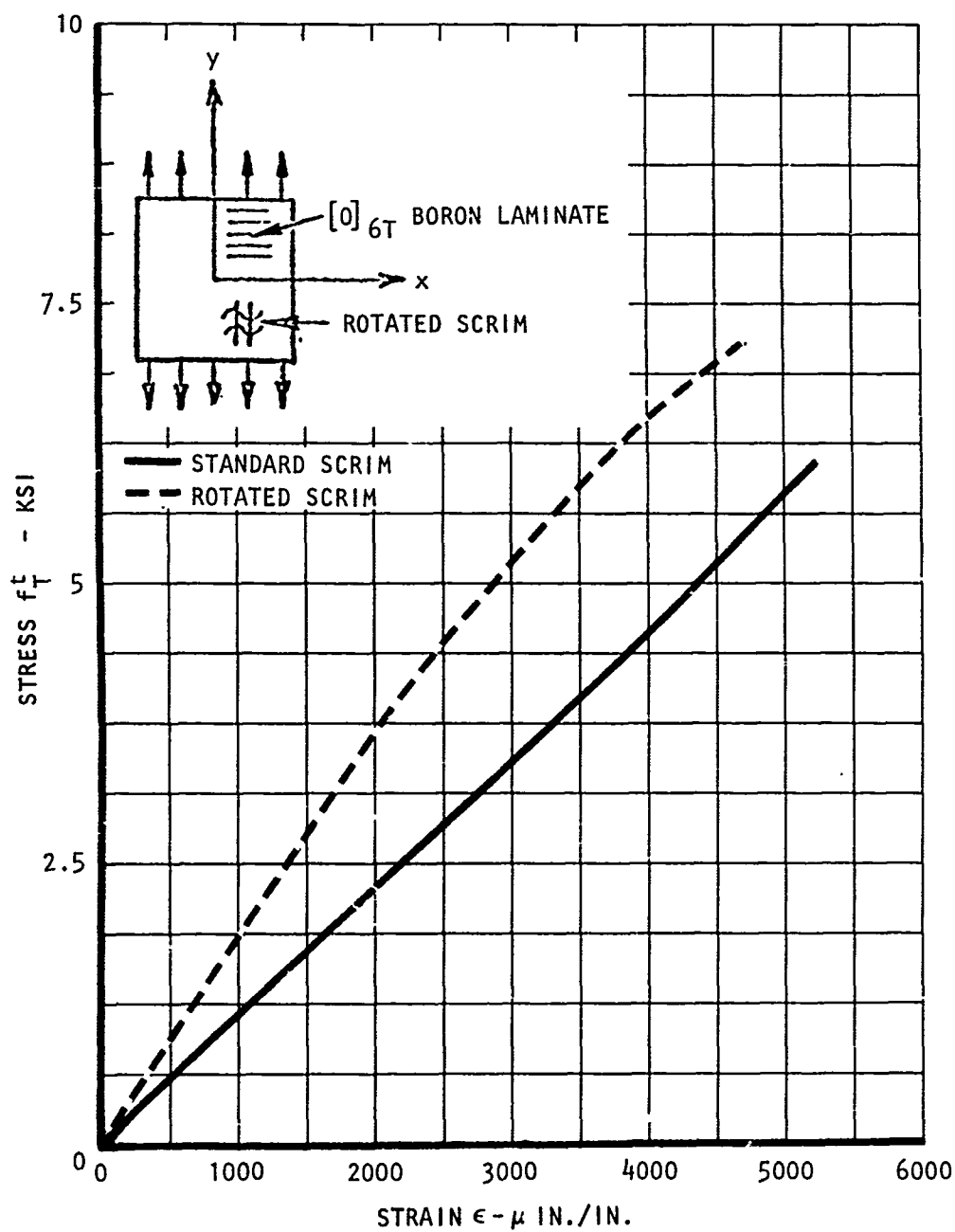


Figure 44. Rotated Scrim Transverse Tension Stress-Strain Curve Comparison With Non-Rotated Data for Narmco 5505 at 350°F

SECTION IV

BASIC ALLOWABLE PROGRAM

CONSTITUENTS

Mechanical properties of the matrix and the scrim cloth materials were investigated to develop reliable data for these constituents to support the laminate property prediction techniques which are based on constituent data.

MATRIX RESIN

Mechanical and physical properties of the Narmco 2387 resin, including filler material, were determined at room temperature and at 350° F, as shown in the test program outlined in table L. Specimens were cast and machined to final configuration to provide "bulk type" matrix property data.

A special cure cycle was followed to minimize the exotherm problem and to cast resin specimens as void-free as possible. The preheated resin was shaped and cut into a rectangle preparatory to placement in the mold. The resin was placed in a circulating air oven at room temperature, then the oven temperature was gradually raised to 200° F. The specimen material was maintained at 200° F for 20 hours, followed by gradual heating for 2-hour dwell steps at 300° F and 350° F. The sequence of casting the Narmco 2387 resin and the configuration of the machined tensile specimens is shown in figure 45.

A 15-ply unidirectional boron/epoxy laminate was laid up from Narmco lot 364 roll 1 and processed in accordance with the aforementioned cure cycle (except cure pressure was 85 psi) to compare resin cure cycle properties with standard laminate properties. The laminate specimen interlaminar shear, longitudinal, and transverse flexure room temperature test data are shown in table LI, together with typical standard cure laminate specimen data.

Laminate strengths using the special resin cure cycle are not equivalent in all cases to those of a standard laminate. Although the transverse flexural strengths are equal, the special (long) resin cure cycle reduces the longitudinal flexural and interlaminar shear strengths by about 8 percent. Since bulk matrix specimens require a special cure and this cure, when applied to laminates, does not develop equivalent properties, the bulk matrix data must be used with due recognition of this fact. Not only the cure process and resulting properties are different, but also the "in situ" strength of the matrix may not be fully reflected by the bulk data.

TABLE L. RESIN CHARACTERIZATION TEST PROGRAM FOR NARMCO 2387 RESIN WITH FILLER

Type Test	Specimen Type and Size	Number of Specimens	Temperature	Instrumentation
Tension	ASTM, D638, Type 1 3/4 x 8.5 in.	5 4	RT 350° F	0°, 90° gages on all specifications
Coefficient of thermal expansion	(Tension specimen)	(1)*	0-350° F	0°, 90° gages
Compression	ASTM, D695 1/2 x 1/2 x 2 in.	3 3	RT 350° F	0°, 90° strain gages on all specimens
Shear	Slotted picture-frame jig 6 x 6 in.	1 1	RT 350°F	Three-leg rosette Three-leg rosette
Fatigue	ASTM, D638, Type 1 (same as tension)	7 (R = 0.1 at 7 load levels)	RT	No instrumentation
Creep	ASTM, D638, Type 1 (same as tension)	3 (at three load levels)	350° F	One 0° gage per specification
Total	---	27 + (1)	---	---
* Conducted using one of the tensile specimens				

The following boron-epoxy laminates using the resin cure cycle were tested to verify equivalence of the resin cure and standard laminate cure cycles:

Three longitudinal flexure coupons at RT
 Three transverse flexure coupons at RT
 Three interlaminar shear coupons at RT



Figure 45. Narmco 2387 Cast Resin Blanks and Tensile Specimens

TABLE LI. RESIN CHARACTERIZATION - 15-PLY UNIDIRECTIONAL LAMINATE TEST RESULTS

Type Test	Special Resin Cure Cycle *	Standard Laminate Cure Cycle *
Longitudinal flexure Ksi	210 213 <u>223</u> 215 avg	229 234 <u>234</u> 232 avg
Transverse flexure Ksi	13.5 13.9 <u>13.2</u> 13.5 avg	12.4 13.5 <u>14.4</u> 13.4 avg
Interlaminar shear Ksi	13.9 13.6 <u>13.8</u> 13.8 avg	14.0 15.3 <u>15.9</u> 15.1 avg

* All specimens made from 2387 resin, Narmco Batch 364, Roll No. 1

In addition, for laminate strength prediction based on constituent properties, the filament-to-matrix interface tensile and shear strength should also be considered. Also, the level of residual stress in the matrix material may be a very significant factor in some laminates.

Matrix Tensile Strength

Tensile properties of the bulk 2387 resin matrix were determined using ASTM D368-64T Type I (0.75- x 8.5-inch dog-bone) specimens about 0.135 inch thick. Tensile tests gave unexpectedly low failing stresses for both room temperature and 350° F relative to the published data shown on page 113. Data for the room temperature tests are given in table LII and figures 46 and 47; data for 350° F are given in table LIII and figure 48.

Examination of the fracture surface of the NR/LAD specimens indicated presence of small air bubbles in the cross section. These voids did not result in a significant reduction of section area but could introduce stress concentrations sufficient to explain the lower strengths. To evaluate this consideration, a small bar of resin material cured at Narmco was machined

TABLE LII. RESIN MATRIX STATIC PROPERTY DATA

Material System: Narmco 2387 ResinType Loading: Tension ☒, Comp ☐, Shear ☐, Interlam Shear ☐Type Test Specimen: ASTM D368-64T Type I, 0.135 inch thickSoak at Temp °F for Hr. Test Temp RT °F

Property	Batch No.					
	Spec Ident	1 (1)	2 (1)	3 (1)		Ave.
Stress (Ksi)	F_{pl}	---	2.77	2.92		2.85
	$F_{.85}$	---	---	---		---
	$F_{.70}$	---	---	---		---
	F at $2/3 \epsilon_1^{ult}$	---	3.25	2.82		3.04
	F_{ult}	4.28	4.67	4.10		4.18
Modulus $E, G \times 10^{-6}$	E or G (primary)	0.52	0.50	0.49		0.51
	E' or G' (secondary)	---	---	---		---
Strain in./in.	Proportional Limit	ϵ_1	---	.00570	.00600	.00585
		ϵ_2	---	.00200	.00200	.00200
		ϵ_{45}				
	Ultimate	ϵ_1	---	.01010	.00865	.00937
		ϵ_2	---	---	---	---
		ϵ_{45}				

Actual Specimen Thickness Spec 1: 0.134 in. Spec 2: 0.135 in. Spec 3: 0.127 in.

Resin Density Resin Designation 2387 including glass filler materialManufacturer NarmcoCure Spec Special slow cure simulating NR Spec ST0105LA0007Comments:

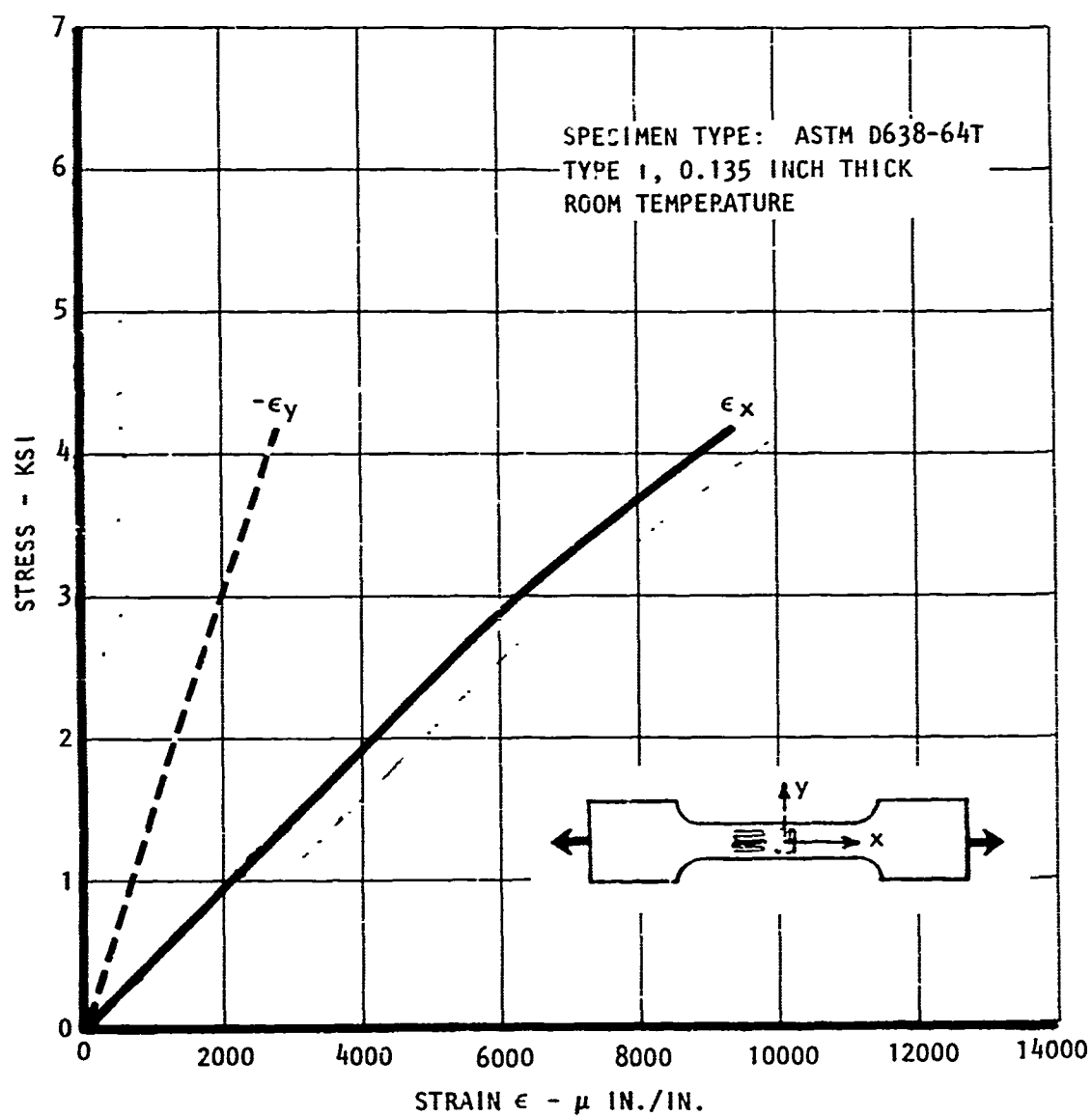


Figure 46. Narmco 2387 Resin RT Tension Stress-Strain Curve

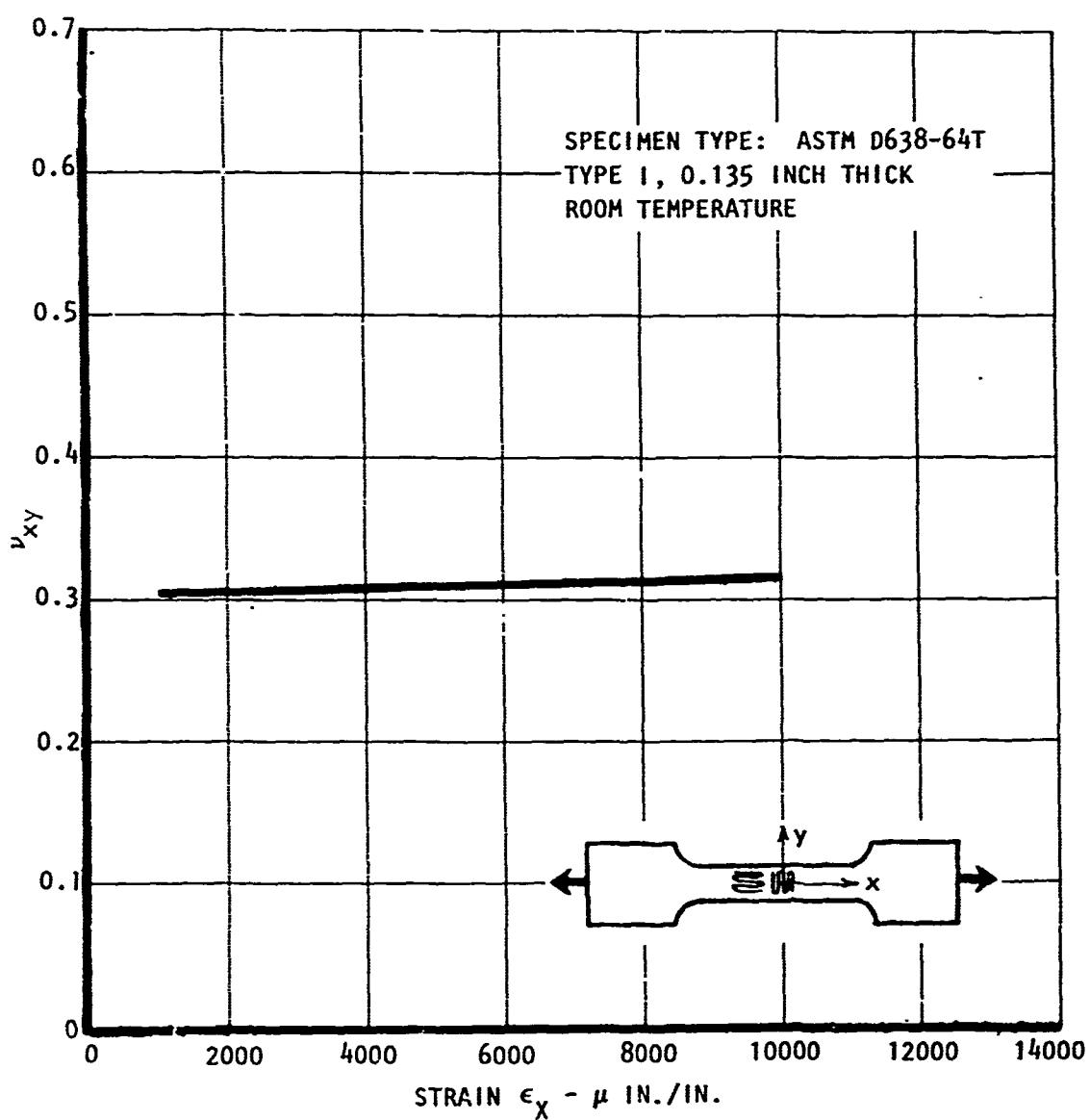


Figure 47. Narmco 2387 Resin RT Poisson's Ratio

TABLE LIII. RESIN MATRIX STATIC PROPERTY DATA

Material System: Narmco 2387 ResinType Loading: Tension ☒, Comp ☐, Shear ☐, Interlam Shear ☐Type Test Specimen: ASTM D638-64T Type I, 0.135 in. thickSoak at Temp - °F for - Hr. Test Temp 350 °F

Property		Batch No.						
		Spec Ident	1	2	3			Ave.
Stress (Ksi)	F _{pl}		1.13	1.13	1.13			1.13
	F _{.85}		---	---	---			---
	F _{.70}		---	---	---			---
	F at 2/3 ϵ_1^{ult}		2.39	2.70	2.70			2.60
	F _{ult}		3.08	3.12	3.22			3.14
Modulus E, Gx10 ⁻⁶	E or G (primary)		.17	.130	.166			.156
	E' or G' (secondary)		---	---	---			---
Strain in./in.	Proportional Limit	ϵ_1	.00690	.00720	.00720			.00711
		ϵ_2	---	---	---			---
		ϵ_{45}						
	Ultimate	ϵ_1	.03180	.03720	.04320			.03740
		ϵ_2	---	---	---			---
		ϵ_{45}						
Actual Specimen Thickness <u>Spec 1: 0.135 in.; Spec 2: 0.138 in.;</u> <u>Spec 3: 0.132 in.</u>								
Resin Density _____								
Resin Designation <u>2387 including glass filler material</u> Manufacturer <u>Narmco</u>								
Cure Spec <u>Special slow cure simulating NR Spec ST0105LA0007</u>								

Comments: _____

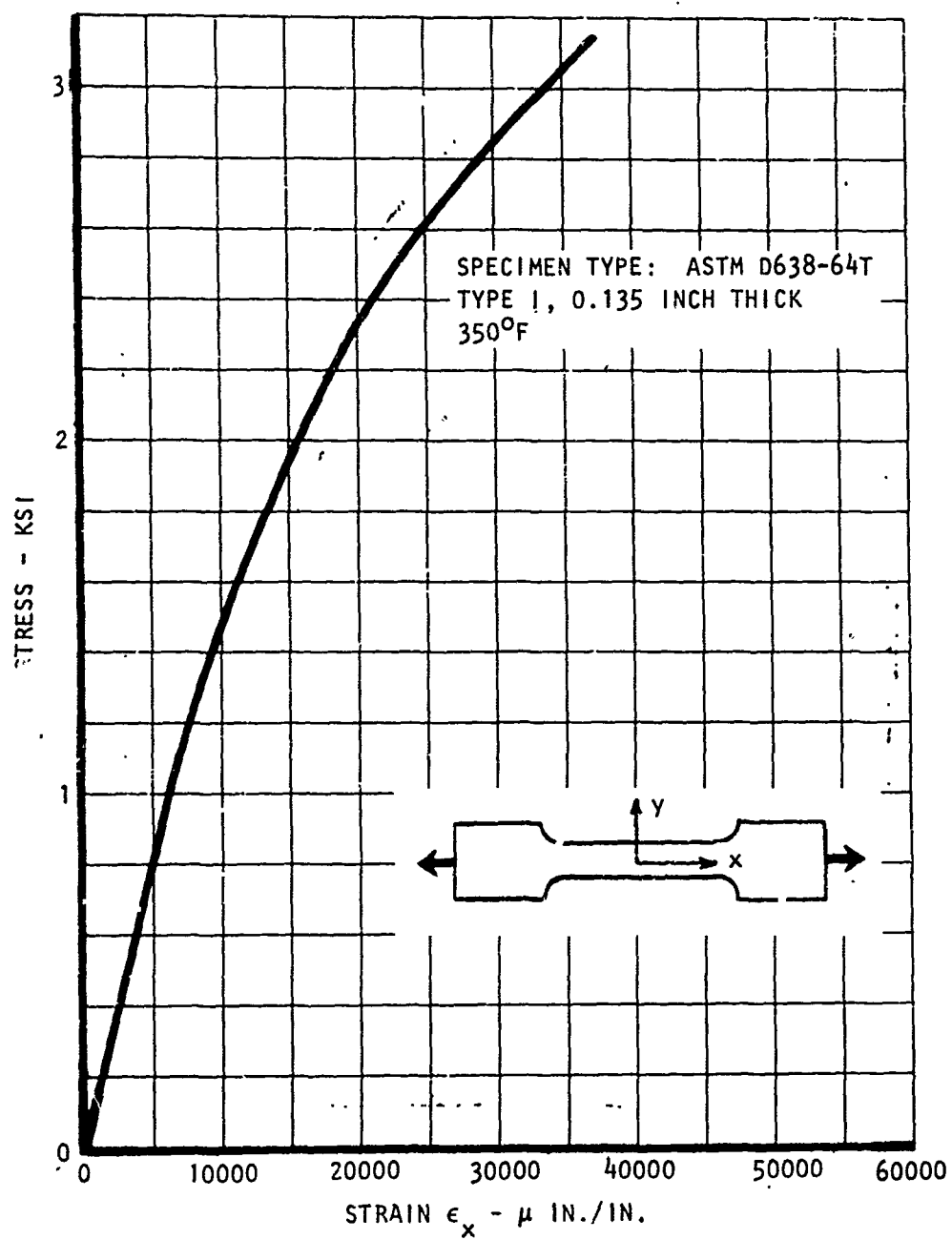


Figure 48. Narmco 2387 Resin 350°F Tension Stress-Strain Curve

into small circular tensile specimens as shown in figure 49. This material had no observable voids. During machining, one end was chipped as shown, but was bonded prior to test. Test preparation also included wrapping the grip area with several layers of glass fabric.

The tensile test of the first Narmco specimen resulted in data similar to those obtained from the NR cast material. Investigation into the cure cycles used indicated that data reported from other sources and shown below were based on material which had been postcured beyond the 2 hours at 350° F used in the NR/LAD process.

The remaining Narmco specimen was then postcured for 4 hours at 350° F. This was accompanied by a very noticeable darkening of the resin color. The postcured specimen failed at a stress level over twice that of the material without postcure. A data sheet (table LIV) and stress-strain plot (figure 50) give properties obtained on the postcured Narmco specimen.

To determine the effect of postcure on NR/LAD cast specimens, three specimens originally scheduled for fatigue testing were postcured 4 hours at 350° F and then static tested, 2 at room temperature and one at 350° F. Results of these tests are shown in tables LV and LVI and figures 51 and 52. A summary of these results with previous tensile values is given below.

Temperature	NR/LAD Cast Material		Narmco Cast Material		AVCO Reported	Narmco Reported
	No Postcure	Postcured at 350° F	No Postcure	Postcured at 350° F		
RT	4,280* 4,680* 4,100* 4,180 avg	4,670* 7,550*	3,900	7,830	8,800	5,300 to 7,050
350° F	3,080* 3,120* 3,220* 3,140 avg	2,879*	---	---	3,800	---

* Numerous spherical voids (gas bubbles) throughout specimen

The variation in the room temperature tensile strengths of the postcured material is believed due to the presence of the spherical voids caused by the bubbles which formed during cure. Unfortunately, all the resin specimens were subject to this condition, and it is present in varying degrees throughout



Figure 49. Cylindrical Namco 2387 Resin Tension Coupon

TABLE LIV. RESIN MATRIX STATIC PROPERTY DATA

Material System: Narmco 2387 Resin

Type Loading: Tension ☒, Comp ☐, Shear ☐, Interlam Shear ☐

Type Test Specimen: Cylindrical Tensile Coupon, 0.2430 in. diameter

Soak at Temp °F for Hr. Test Temp RT °F

Property		Batch No.					
		Spec Ident					Ave.
Stress (ksi)	F _{p1}		1.95				1.95
	F _{.85}		7.65				7.65
	F _{.70}		---				---
	F at 2/3 ϵ_1^{ult}		5.75				5.75
	F _{ult}		7.83				7.83
Modulus E, Gx10 ⁻⁶	E or G (primary)		0.48				0.48
	E' or G' (secondary)		---				---
Strain in./in.	Proportional Limit	ϵ_1	0.00400				0.00400
		ϵ_2	---				---
		ϵ_{45}	---				---
	Ultimate	ϵ_1	0.0193				0.0193
		ϵ_2	---				---
		ϵ_{45}	---				---

Actual Specimen Thickness Specimen cross-sectional diameter: 0.2430 in.

Resin Density

Resin Designation 2387 including glass filler material

Manufacturer Narmco

Cure Spec 4 hours at 350° F

Comments: Material cast at Narmco and Postcured at NR/LAD

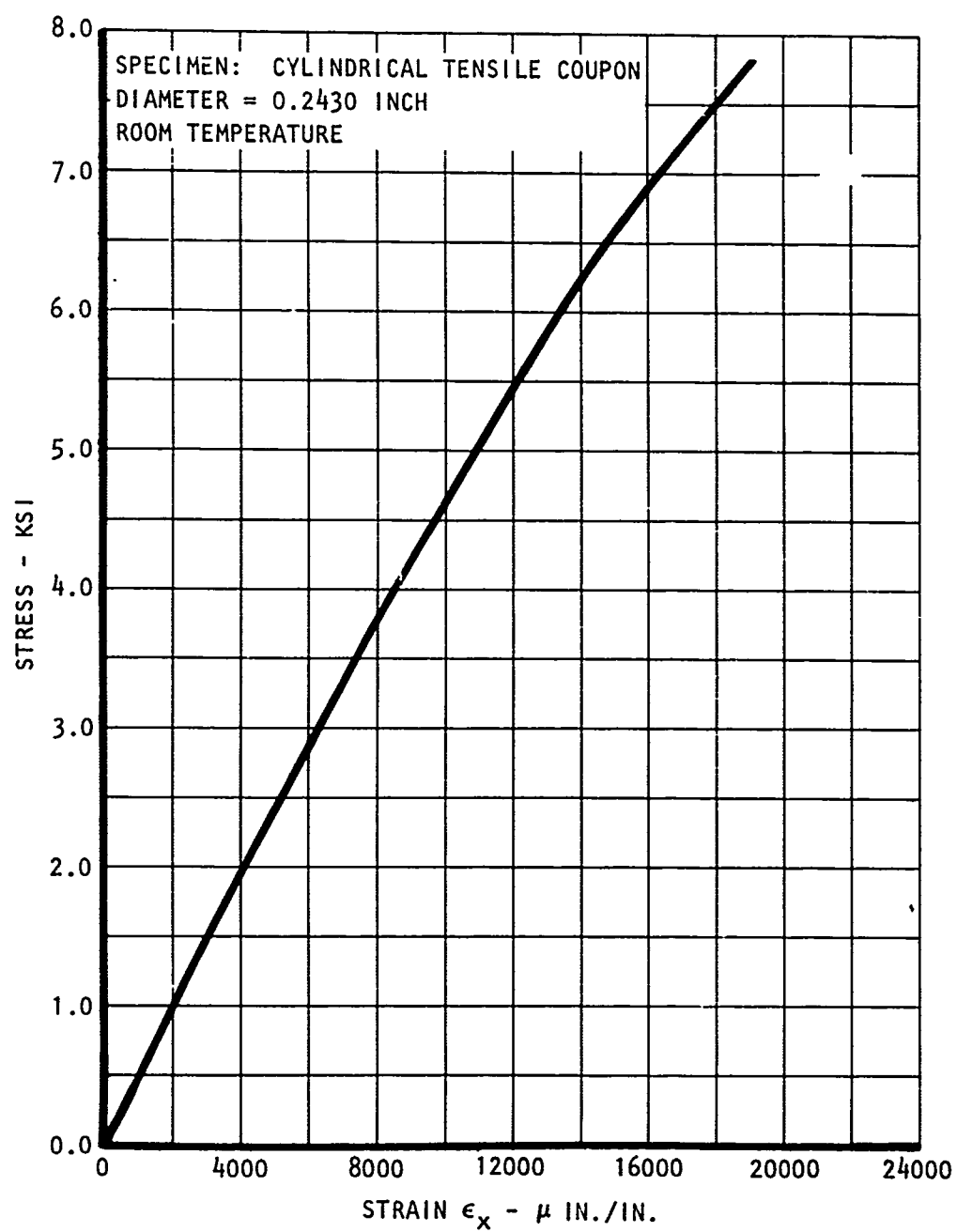


Figure 50. Narmco 2387 Resin Tension Stress-Strain Curve

TABLE LV. RESIN MATRIX STATIC PROPERTY DATA

Material System: Narmco 2387 ResinType Loading: Tension ☒, Comp ☐, Shear ☐, Interlam Shear ☐Type Test Specimen: ASTM D368-64T Type ISoak at Temp - °F for - Hr. Test Temp RT °F

Property		Batch No.					
		Spec Ident	1 (1)		2		Ave.
Stress (Ksi)	F _{p1}		3.05		-		-
	F _{.85}		-		-		-
	F _{.70}		-		-		-
	F at 2/3 ϵ_1^{ult}		3.20		-		-
	F _{ult}		4.67		7.55		6.11
Modulus E, Gx10 ⁻⁶	E or G (primary)		.47		.51		.49
	E' or G' (secondary)		-		-		-
Strain in./in.	Proportional Limit	ϵ_1	.0064		-		-
		ϵ_2	-.0021		-		-
		ϵ_{45}	-		-		-
	Ultimate	ϵ_1	.0102		.0168		.0135
		ϵ_2	-.0032	(2)	-		-
		ϵ_{45}	-		-		-

Actual Specimen Thickness Spec 1: 0.136 in.; Spec 2: 0.125 in.

Resin Density _____

Resin Designation 2387 including glass filler material

Manufacturer Narmco

Cure Spec (3) Special slow cure simulating NR Spec ST0105LA0007

Comments: (1) Strain gaged (2) Extrapolated (3) Postcured 4 hours at 350° F
Numerous small spherical voids throughout specimens

TABLE LVI. RESIN MATRIX STATIC PROPERTY DATA

Material System: Narmco 2387 ResinType Loading: Tension ☒, Comp ☐, Shear ☐, Interlam Shear ☐Type Test Specimen: ASTM D368-64T Type I, 0.137 in. thickSoak at Temp 350°F for 0.2 Hr. Test Temp 350°F

Property		Batch No.						
		Spec Ident	2					Ave.
Stress (Ksi)	F_{pl}		-					
	$F_{.85}$		-					
	$F_{.70}$		-					
	F at $2/3 \epsilon_1^{ult}$		-					
	F_{ult}		2.89					
Modulus $E, G \times 10^{-6}$	E or G (primary)		.12					
	E' or G' (secondary)		-					
Strain in./in.	Proportional Limit	ϵ_1		-				
		ϵ_2		-				
		ϵ_{45}		-				
	Ultimate	ϵ_1		.046				
		ϵ_2		-				
		ϵ_{45}		-				
Actual Specimen Thickness <u>0.137 in.</u>								
Resin Density _____								
Resin Designation <u>2387 including glass filler material</u>								
Manufacturer <u>Narmco</u>								
Cure Spec <u>*Special slow cure simulating NR Spec ST0105LA0007</u>								

Comments: * Postcured 4 hours at 350° FNumerous small spherical voids throughout specimens

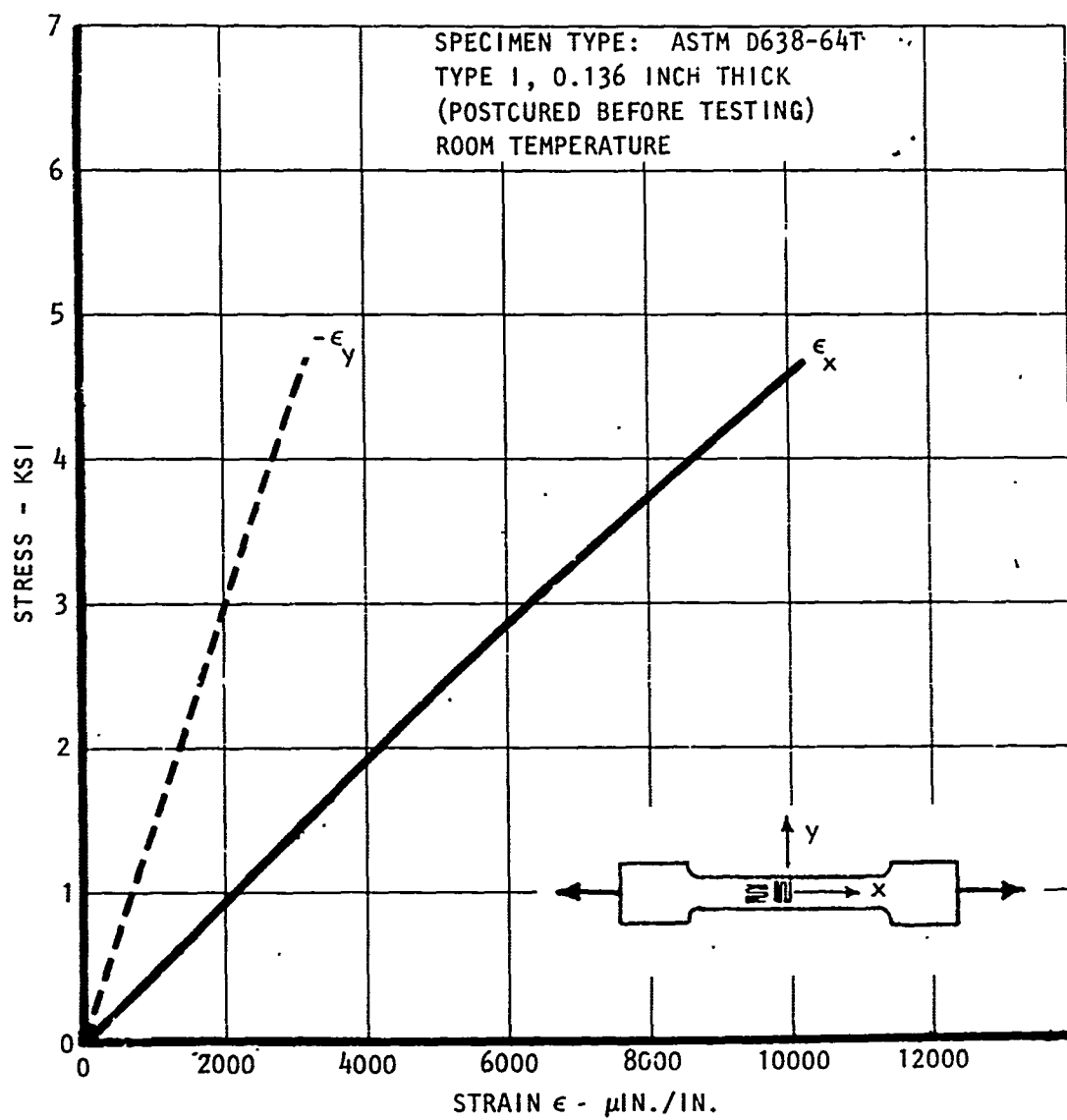


Figure 51. Narmco 2387 Resin Tension Stress Strain Curve

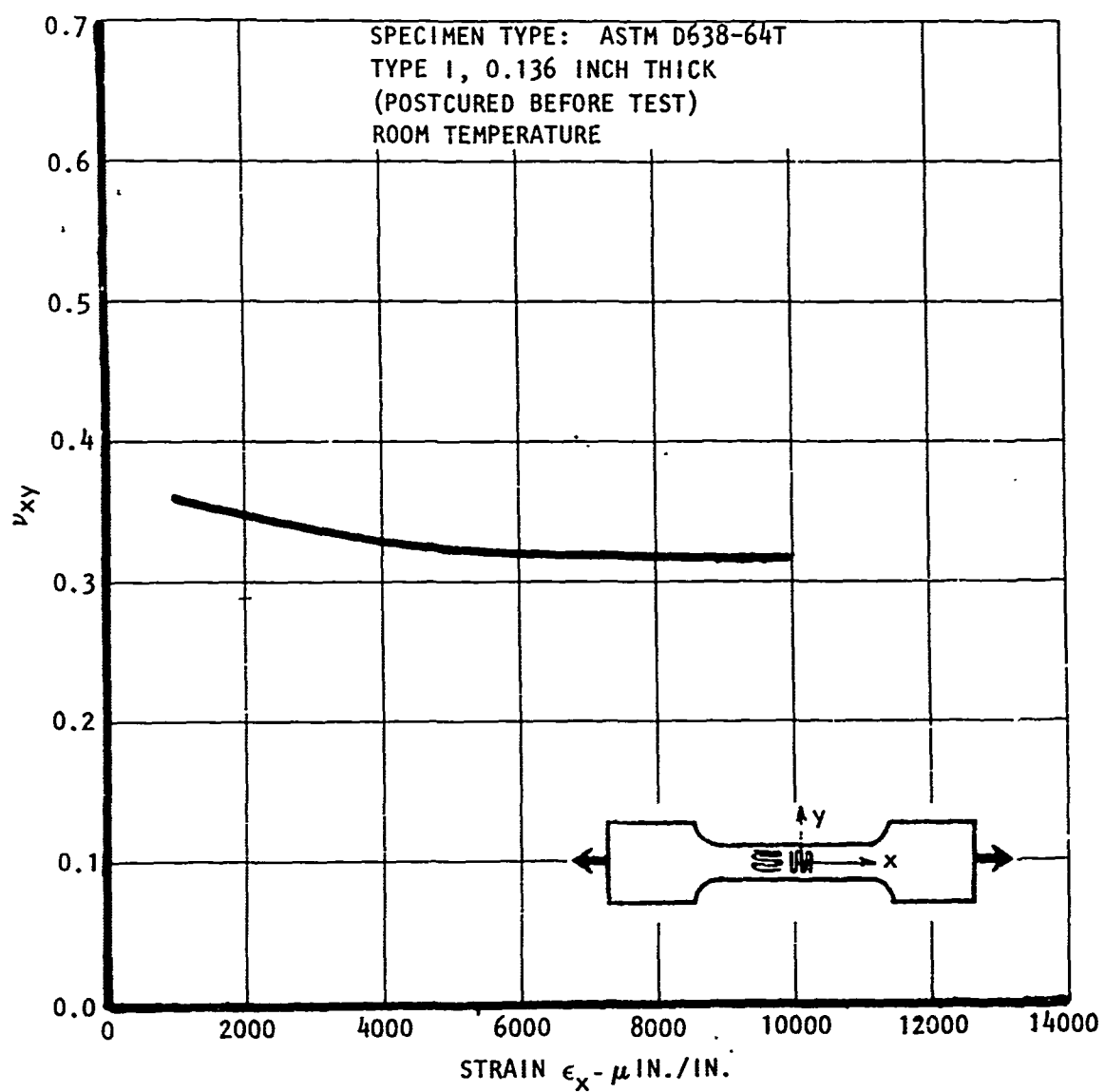


Figure 52. Narmco 2387 Resin Poisson's Ratio

the specimens. Close-spaced voids or concentrations of voids in a local area is suspected to be the cause of the random low values.

As an additional check on the tensile strength and the possible influence of the gas bubble voids, three of the tensile specimen ends were tested in flexure. This provided a relatively localized zone of the critical tensile stress and a much lower probability of having a bubble in the maximum stress region. The 2-inch-span flexural loading fixture with a central load was used. Test results were as follows:

Specimen	Temperature	Failing Load	Central Deflection	Calculated* Max Stress	Calculated Deflection
1	RT	45.7 lb	0.128 in.	14,740 psi	0.143 in.
2	RT	39.9 lb	0.115 in.	12,943 psi	0.125 in.
3	350°	21.9 lb	(Not recorded)	7,300	---

*Based on $f = \frac{MC}{I}$; $\delta = \frac{Wl^3}{48EI}$ with $E = 510,000$ psi

Determining the cause of the surprisingly large difference between tensile and flexural results was beyond the scope of the program. On the basis of the room temperature stress-strain curves (for tension and compression), a large bending form factor did not appear probable, and the difference in results was greater than expected for bubble-type concentration factors.

Matrix Compression Strength

Compression properties of the bulk 2387 resin material were developed using a 1/2- x 1/2- x 2-inch specimen loaded in the 2-inch direction. Room temperature properties are listed in table LVII and plotted in figure 53.

Elevated temperature (350° F) compression properties are listed in table LVIII and plotted in figure 54. One specimen of this group was strain-gaged, but readings after heating the specimen exceed the SR-4 recorder range, so no strain gage data are available, and all deformation was based on extensometer measurements.

TABLE LVII. RESIN MATRIX STATIC PROPERTY DATA

Material System: Narmco 2387 ResinType Loading: Tension ☐, Comp ☒, Shear ☐, Interlam Shear ☐Type Test Specimen: 1/2 X 1/2 X 2 in. compressionSoak at Temp _____ °F for _____ Hr. Test Temp RT °F

Property		Batch No.						
		Spec Ident	1	2	3 (1)			Ave.
Stress (Ksi)	pp1		3.60	5.28	8.88			5.92
	F _{.85}		13.0	14.6	16.2			14.6
	F _{.70}		-	20.7	-20.3			20.5
	F at 2/3 ϵ_1^{ult}		-	22.0	20.7			21.3
	F _{ult}		25.0	24.2	23.5			24.2
Modulus E, Gx10 ⁻⁶	E or G (primary)		.570	.576	.440			.5287
	E' or G' (secondary)		-	-	-			-
Strain in./in.	Proportional Limit	ϵ_1	-.0054	-.0087				-.0071
		ϵ_2	-	-	-			-
		ϵ_{45}	-	-	-			-
	Ultimate	ϵ_1	-	-.107	-.105			-.106
		ϵ_2	-	-	-			-
		ϵ_{45}						
Actual Specimen Thickness <u>0.50 in.</u>								
Resin Density _____								
Resin Designation <u>2387 including glass filler material</u>								
Manufacturer <u>Narmco</u>								
Cure Spec <u>Special slow cure simulating NR Spec ST0105LA0007</u>								

Comments: (1) Strain-gaged

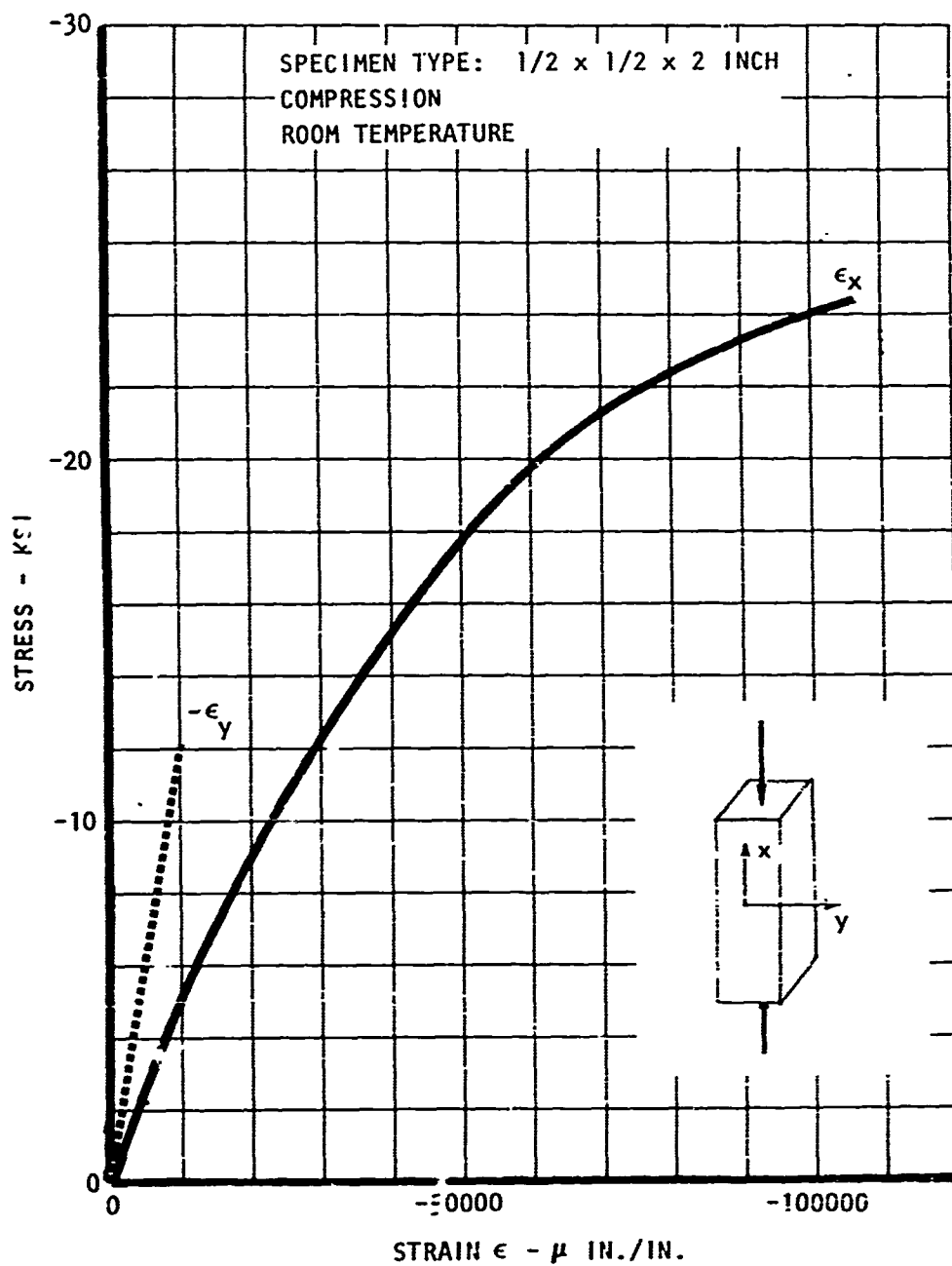


Figure 53. RT Compression Stress-Strain Plot of Narmco 2387 Resin

TABLE LVI'I. RESIN MATRIX STATIC PROPERTY DATA

Material System: Narmco 2387 ResinType Loading: Tension ☐, Comp ☒, Shear ☐, Interlam Shear ☐Type Test Specimen: 1/2 X 1/2 X 2 in. compressionSoak at Temp 350°F for 0.17 Hr. Test Temp 350°F

Property		Batch No.						
		Spec Ident	4	5	6 (1)			Ave.
Stress (Ksi)	FP1		2.04	2.04	2.16			2.08
	F _{.85}		4.4	3.5	3.8			3.9
	F _{.70}		4.6	4.3	4.6			4.5
	F at 2/3 ϵ_1^{ult}		10.7	11.4	10.1			10.7
	F _{ult}		17.3	18.4	14.7			16.8
Modulus $E, G \times 10^{-6}$	E or G (primary)		.20	.16	.16			.17
	E' or G' (secondary)		-	-	-			-
Strain in./in.	Proportional Limit	ϵ_1	-.0108	-.0144	-.0150			-.0134
		ϵ_2	-	-	-			-
		ϵ_{45}	-	-	-			-
	Ultimate	ϵ_1	-.282	-.316	-.279			-.292
		ϵ_2	-	-	-			-
		ϵ_{45}	-	-	-			-
Actual Specimen Thickness <u>0.50 in.</u>								
Resin Density _____								
Resin Designation <u>2387 including glass filler material</u>								
Manufacturer <u>Narmco</u>								
Cure Spec <u>Special slow cure simulating NR Spec ST0105LA0007</u>								

Comments: (1) Strain-gaged specimen, but gage readings exceeded recorder

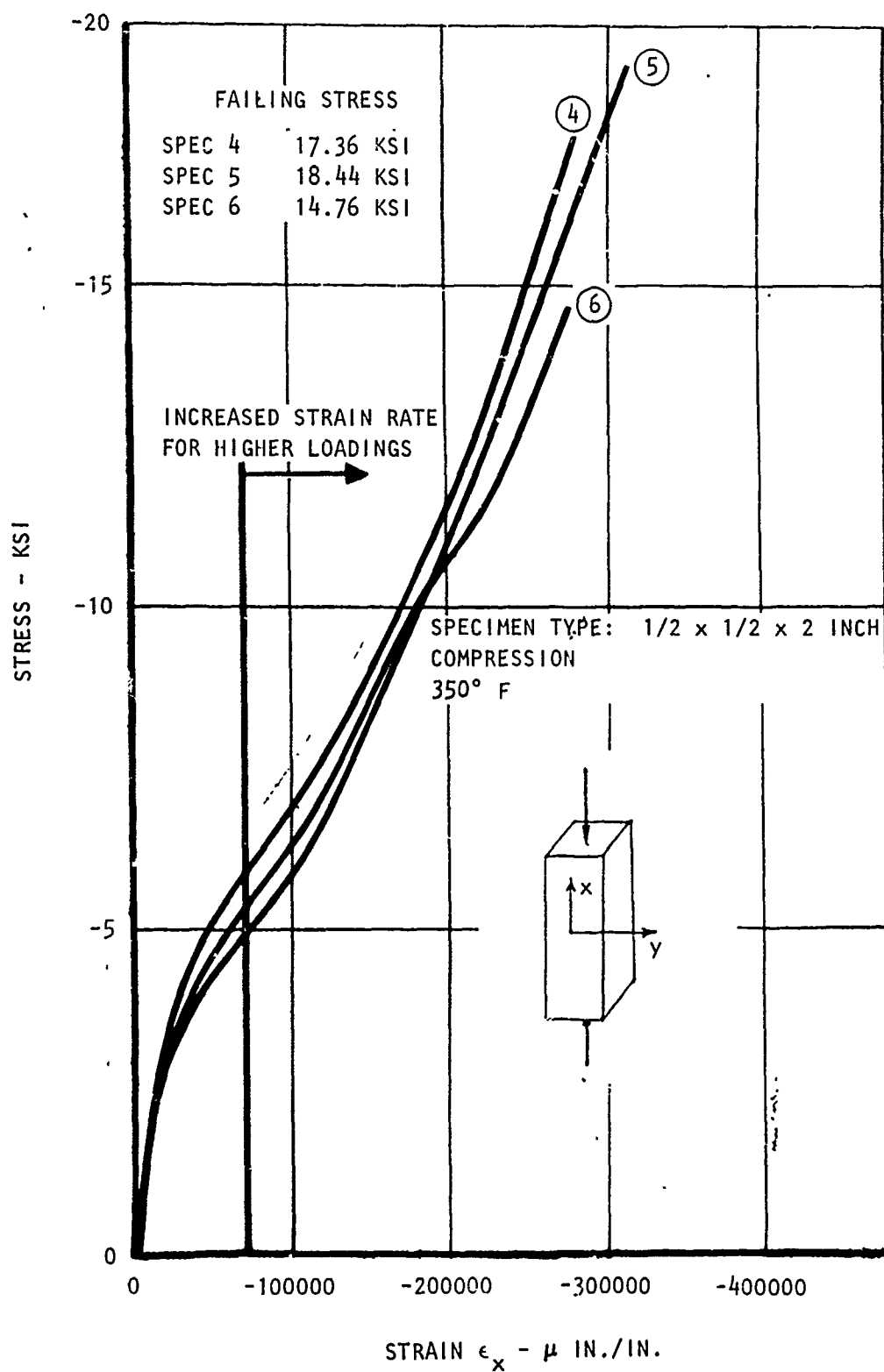


Figure 54. 350° F Compression Stress-Strain Plot of Narmco 2387 Resin

Plots of strain data above 80,000 μ in./in., or about 5,000 psi, indicated a rather erratic response (figure 54). Further checks of these tests indicated that the material appeared to creep above this loading, and the test engine increased the rate of loading to compensate. Precise loading rates are not available for these curves.

The manner of failure was rather unusual. The specimen appearance was unchanged up to failure, which occurred catastrophically with a disintegration of the specimen into particles and powder. The mode of failure was explosive in nature, and the result was as though the specimen had been hit with a hammer.

Poisson's ratio for the room temperature specimen, based on strain gage readings, is plotted in figure 55.

Matrix Shear Strength

Shear properties of the bulk 2387 material were developed using an in-plane shear testing fixture. The specimen was a single plate of resin approximately 3 x 3 inches and about 0.20 inch thick. The specimen was loaded in a picture-frame, shear-type loading fixture developed at NR/LAD, which applies pure shear to the edge of the test area. This device is shown schematically in figure 56. The principal feature of this fixture is the application of loads by pin-ended links aligned along the edges of the test section. Link loads are delivered to test fixture loading plates, which are in turn bolted to the specimen loading tab doublers (bonded to the specimen face). A typical test setup ready for loading is shown in figure 57.

Strain gage rosettes were placed back-to-back in the test area of the specimen. During the 300° F bake for curing the strain gage bonding for the elevated temperature specimen, the resin fractured at the edge of the test area between adjacent diagonal slots. The reason for the fracture was not apparent but may have resulted from a stress concentration at the end of the slot and some thermally induced strain due to the presence of the bonded aluminum loading doubler on each tab.

The room temperature shear specimen was tested and failed at an unexpectedly low shear stress. The strain gages again indicated that a relatively pure shear had been applied, since the readings at +45° and -45° were equal but of opposite sign, and the 0° gage was near zero. However, one surface of the specimen picked up load earlier and was strained more critically than the other, as noted in the following data.

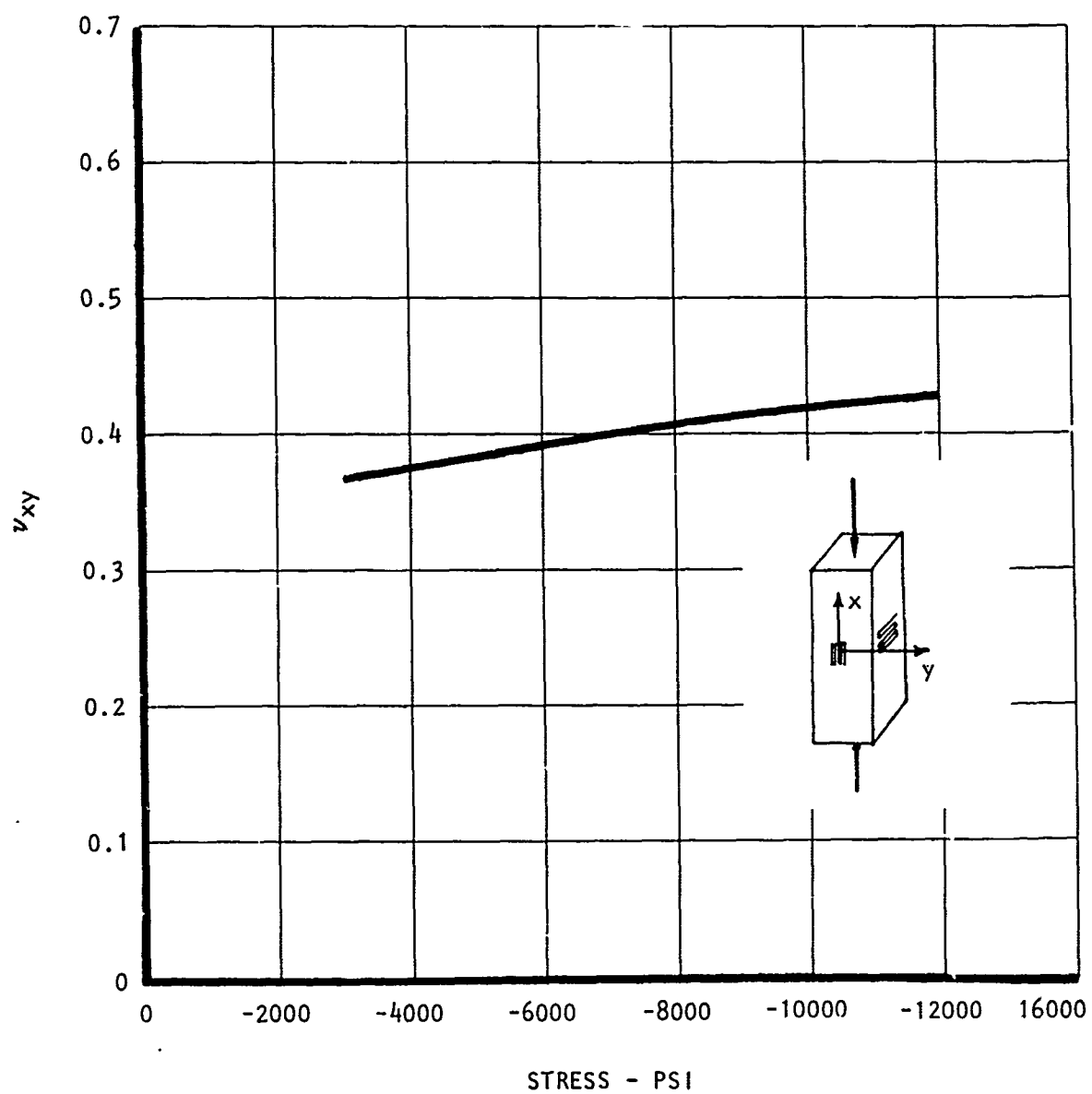


Figure 55. RT Compression Poisson's Ratio for Narmco 2387 Resin

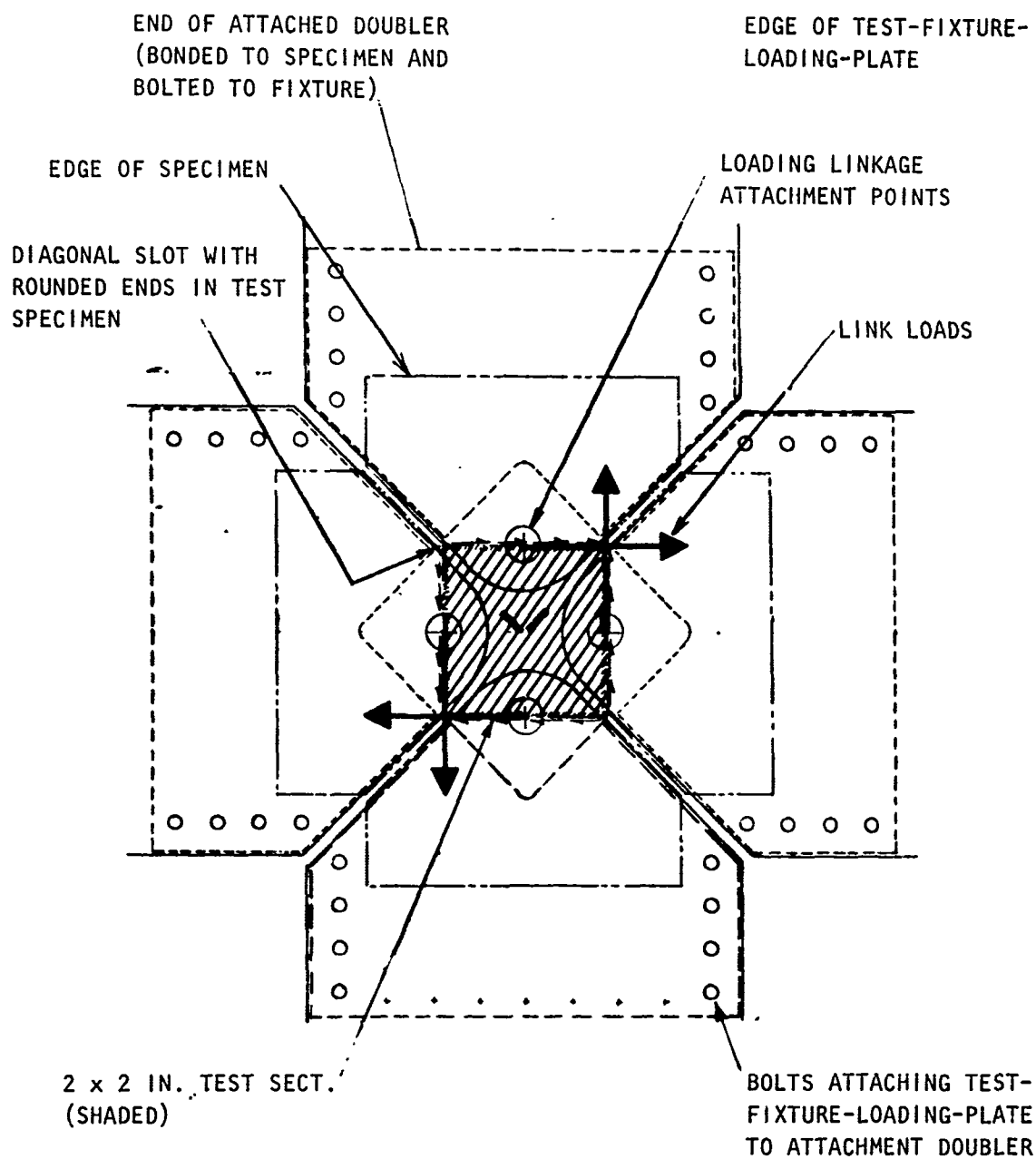


Figure 56. Pure In-Plane Shear Loading Test Fixture Sketch

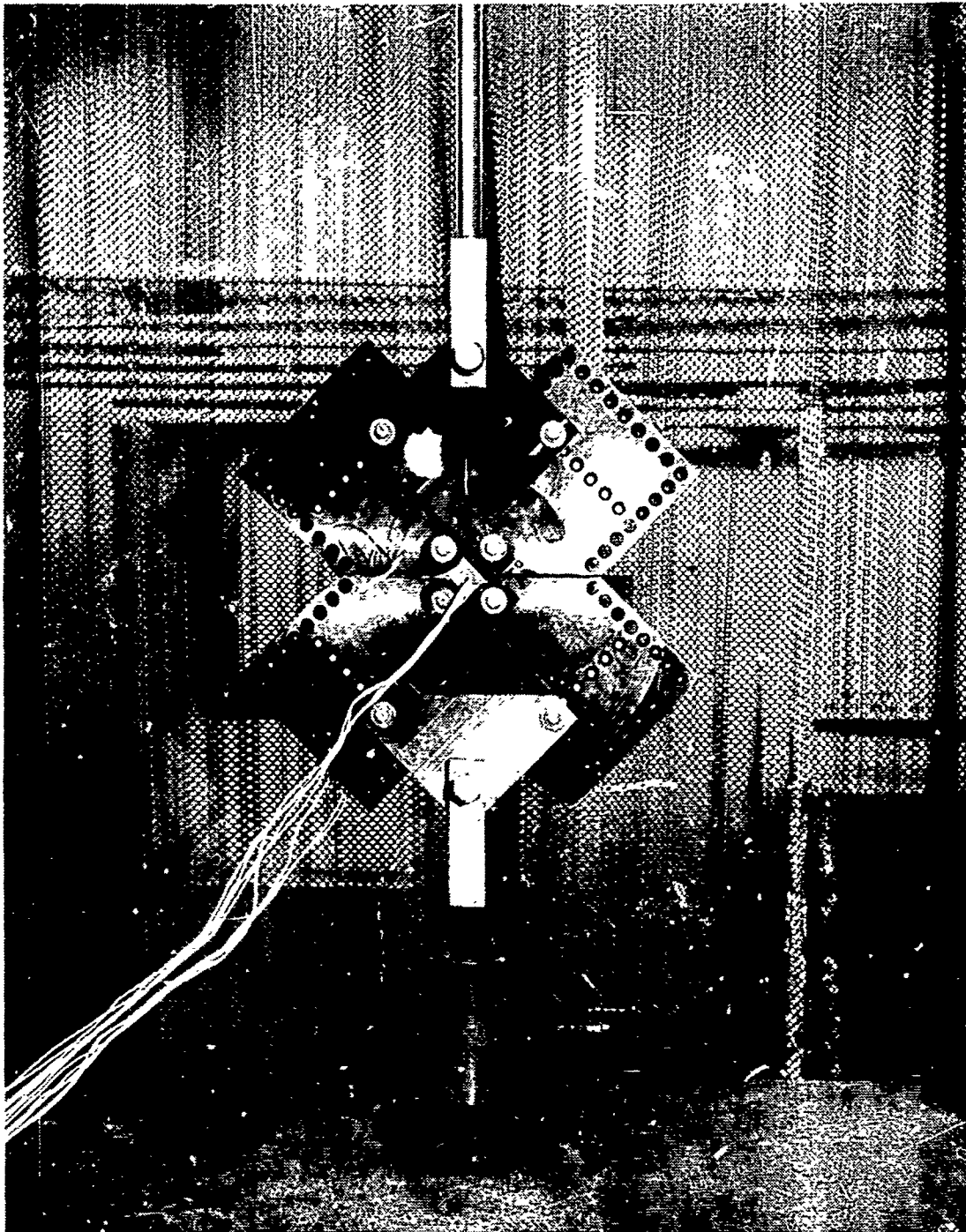


Figure 57. In-Plane Shear Test Set-Up

Load Increment (Pounds)	Rosette Location	Strain Gage Readings - μ in./in.		
		Strain Gage Orientation		
		+45°	0°	-45°
0-50	Side 1	+708	51	-692
	Side 2	-98	-19	+117
50-565	Side 1	+2,483	-76	-2,711
	Side 2	+2,203	-167	-2,138
0-565	Side 1	+3,191	-25	-3,403
	Side 2	+2,105	-186	-2,021

Using the data from the 0-565-pound loading, the critical surface is 1.23 times the average. If this ratio is used, the failing stress on this surface would be (1.23) (1,540), or about 1,900 psi, still well below expected strength, being 1,900/4,180, or 45 percent of the tensile strength of specimens without postcure.

The early failure of this specimen is undoubtedly due to the stress concentration developed at the ends of the diagonal slots. This factor is also indicated by the form of fracture of the test area as illustrated in figure 58.

A data sheet (table LIX) and shear stress versus shear strain plot for the two increments recorded (figure 59) are included, covering the room temperature properties.

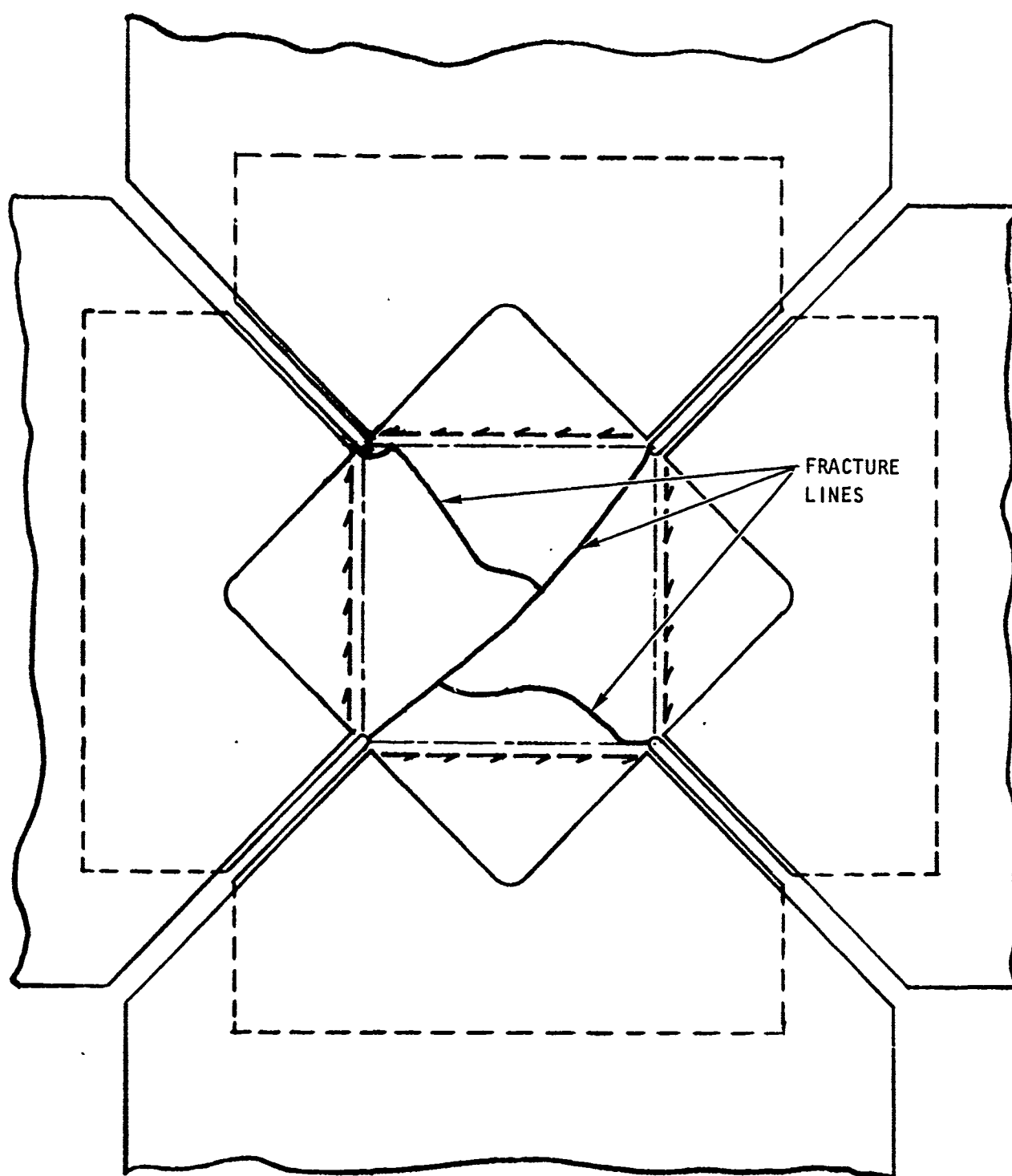


Figure 58. Resin Shear Specimen Diagram Showing Fracture Locations

TABLE LIX. RESIN MATRIX STATIC PROPERTY DATA

Material System: Narmco 2387 ResinType Loading: Tension ☐, Comp ☐, Shear ☒, Interlam Shear ☐Type Test Specimen: Pure Shear Picture-Frame SpecimenSoak at Temp °F for Hr. Test Temp RT

Property	Batch No.						
	Spec Ident	(1)					Ave.
Stress (Ksi)	F _{P1}	-					-
	F _{.85}	-					-
	F _{.70}	-					-
	F at $2/3 \epsilon_1^{ult}$	-					-
	F _{ult}	(2) 1.54					1.54
Modulus E, G x 10 ⁻⁶	E or G (primary)	0.191					0.191
	E' or G' (secondary)	-					-
Strain in./in.	Proportional Limit	ϵ_1	-				-
		ϵ_2					
		ϵ_{45}					
	Ultimate	ϵ_1	0.00825	(3)			0.00825
		ϵ_2					
		ϵ_{45}					

Actual Specimen Thickness = 0.210 in.Resin Density Resin Designation 2387Manufacturer NarmcoCure Spec No post cureComments: (1) Instrumented with back-to-back strain rosettes(2) Premature failure due to stress concentration at slots(3) Extrapolated

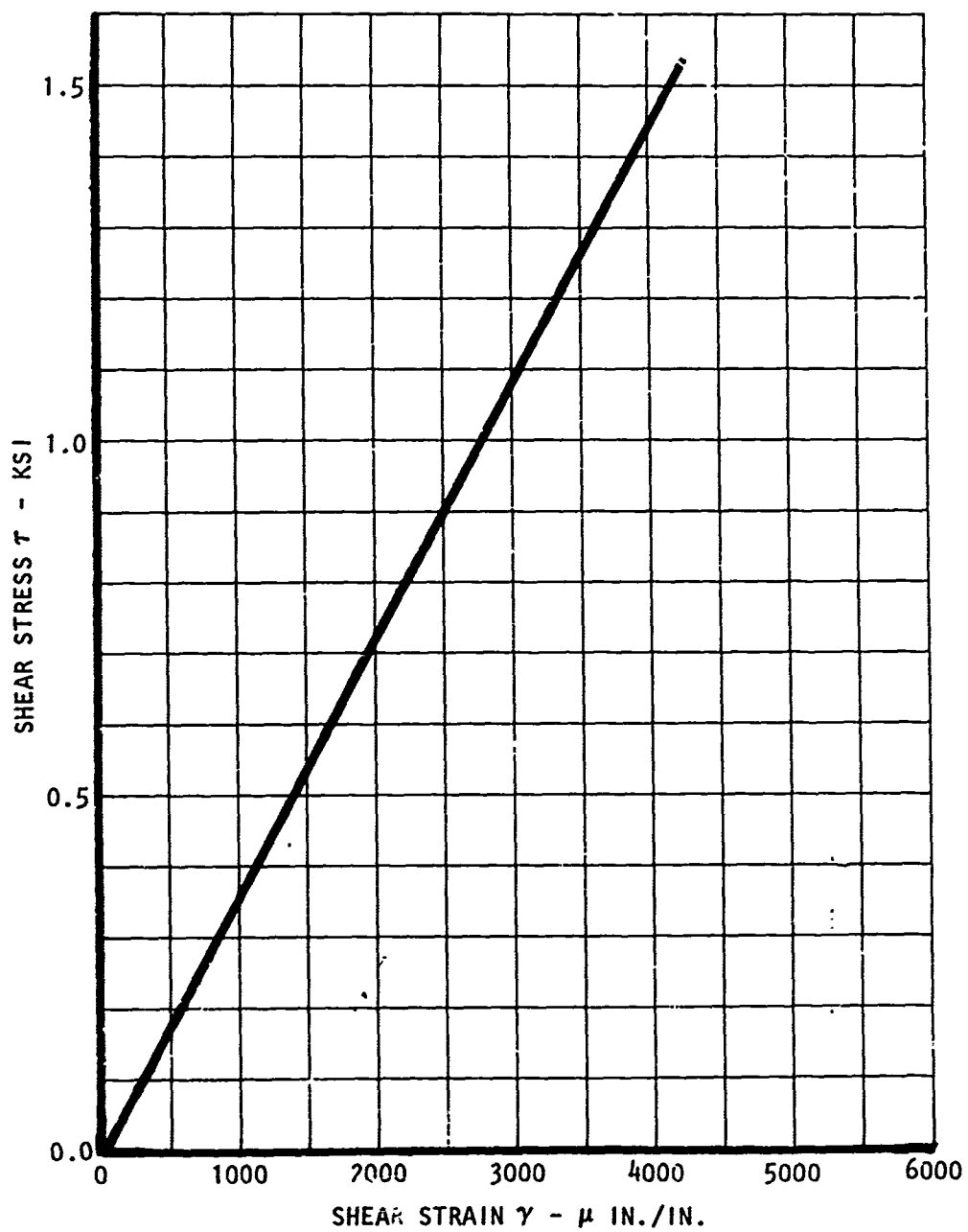


Figure 59. Room Temperature Shear Stress-Strain Plot for Narmco 2387 Resin

Matrix Fatigue Strength

Fatigue strength of the bulk 2387 resin material was determined by using the same type specimen used in the tensile property program. On the basis of results of the tensile testing, it was decided to postcure all specimens 4 hours at 350° F.

Although postcured strengths of the two room temperature specimens differed (4.67 ksi and 7.55 ksi), the lower value was considered to be a "bad" point compared with other sources and a basic strength of 7.26 ksi was chosen for the fatigue test program.

Fatigue specimens were cycled at various stress levels between 40 and 60 percent of this value, using an "R" factor of 0.10. Results were as follows:

<u>Percent Static Strength</u>	<u>Max Stress (ksi)</u>	<u>Cycles to Failure</u>
40	2.85	No failure*
42	3.0	497,050
44	3.2	34,100
45	3.3	104,000
50	3.6	25,350
52	3.8	16,700
61	4.45	1,450

*After 10,397,000 cycles

An S-N plot indicating percentage of static strength (based on 7.26 ksi) versus cycles to failure is shown in figure 60. The consistency of the fatigue data is unexpected, considering the variation of static tensile strength.

The specimen which was cycled at 40 percent without fatigue failure was static tested. Static failure of this specimen occurred at 7.44 ksi, which was above the basic assumed static strength and essentially equal to the best postcured resin test strength of 7.55 ksi.

Matrix Creep Strength

Creep strength of the bulk 2387 resin material was determined by testing three postcured tensile-type specimens at 350° F. Static strength at 350° F for this batch of material (considering casting, curing, and postcuring) was considered to be about 3,000 psi. The initial stress level was 1,000 psi, and on the basis of its short life, the remaining levels were chosen lower. Results were as follows:

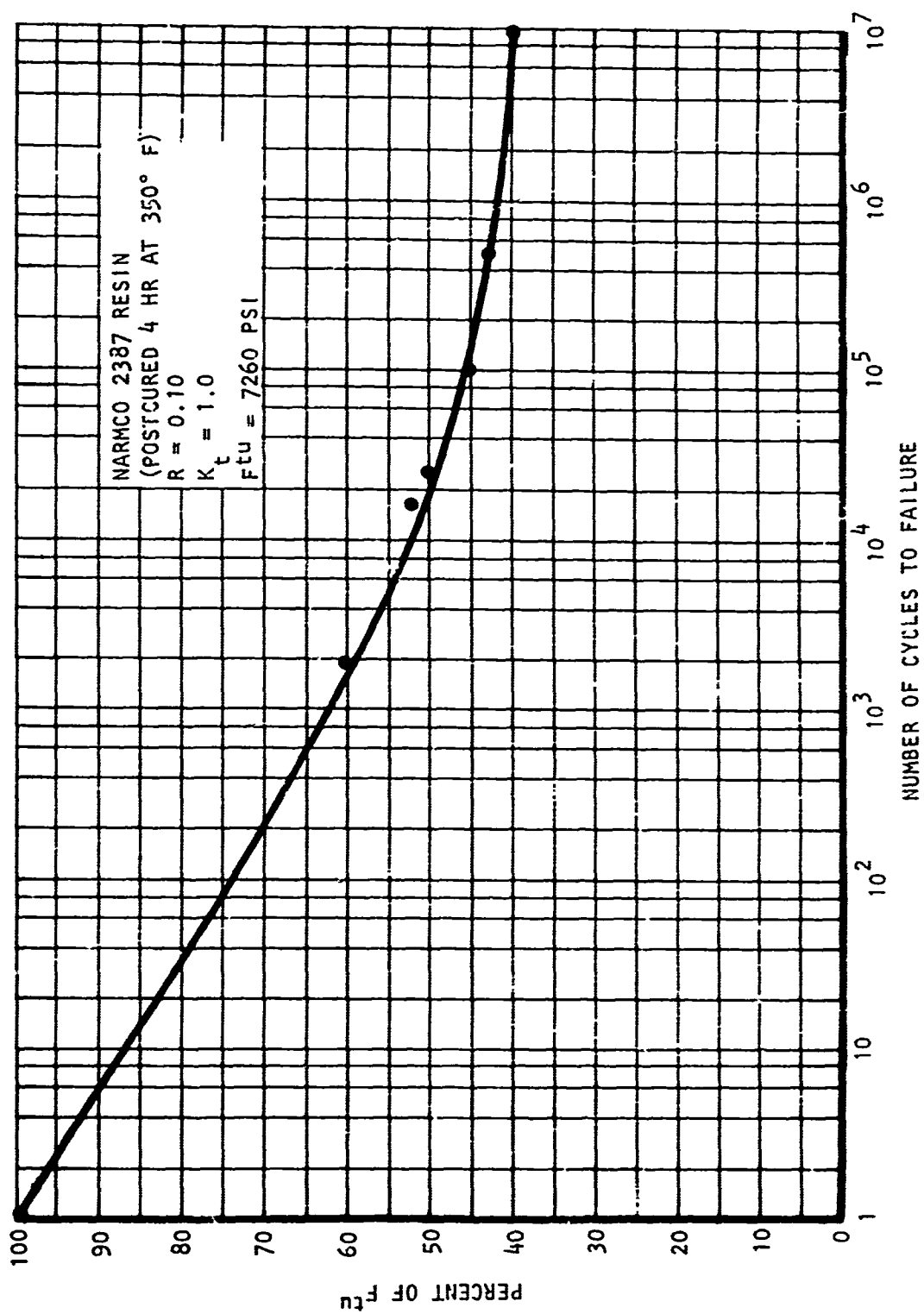


Figure 60. Narmco 2387 Resin Tension S-N Curve - Room Temperature

<u>Specimen</u>	<u>Percent Static Strength</u>	<u>Creep Load Level (psi)</u>	<u>Failing Deformation (in./in.)</u>	<u>Time to Failure (hours)</u>
1	33	1,000	0.080	2.0
2	25	750	0.046	1.1
3	17	500	0.044	3.8

A plot of the total strain versus time after load application is shown for each specimen in figure 61. The second, or 750 psi, specimen appears inconsistent with the others. No reason for the low elongation was evident, but it may have been a result of the minute voids (bubbles) found in this batch of material. All specimens contained these voids to a similar degree as well as could be determined by visual examination.

Matrix Thermal Coefficient of Expansion

Coefficient of thermal expansion values for the bulk 2387 resin were determined by using the broken elevated temperature shear specimen. Readings of the individual legs of the back-to-back rosettes indicated a uniform response in all directions. However, there was some creep apparent above the 300° F temperature level during the first run (probably due to incomplete postcure), resulting in significant zero readings on return to room temperature. A second run, however, gave the same low temperature data and relatively small zero readings on return to room temperature.

Values of the coefficient of thermal expansion were based on the second run and are calculated in the following table. A plot of the values versus temperature is given in figure 62.

<u>Temperature (T)</u> °F	<u>ΔT</u> °F	<u>α_{Gage}</u> (μin./in./°F)	<u>Σε_{Resin}</u> (μin./in.)	<u>Apparent α_{Resin}</u> (μin./in./°F)	<u>Actual* α_{Resin}</u> (μin./in./°F)
72	0	-	-	-	-
100	28	6.05	620	22.1	28.1
150	78	6.26	1,870	24.0	30.2
200	128	6.69	3,220	25.2	31.8
250	178	6.97	4,650	26.1	33.0
300	228	7.22	6,250	27.4	34.6
350	278	7.34	8,250	29.7	37.0

*Average integrated value of α over entire ΔT range between T and room temperature (i.e., not value of α at temperature T)

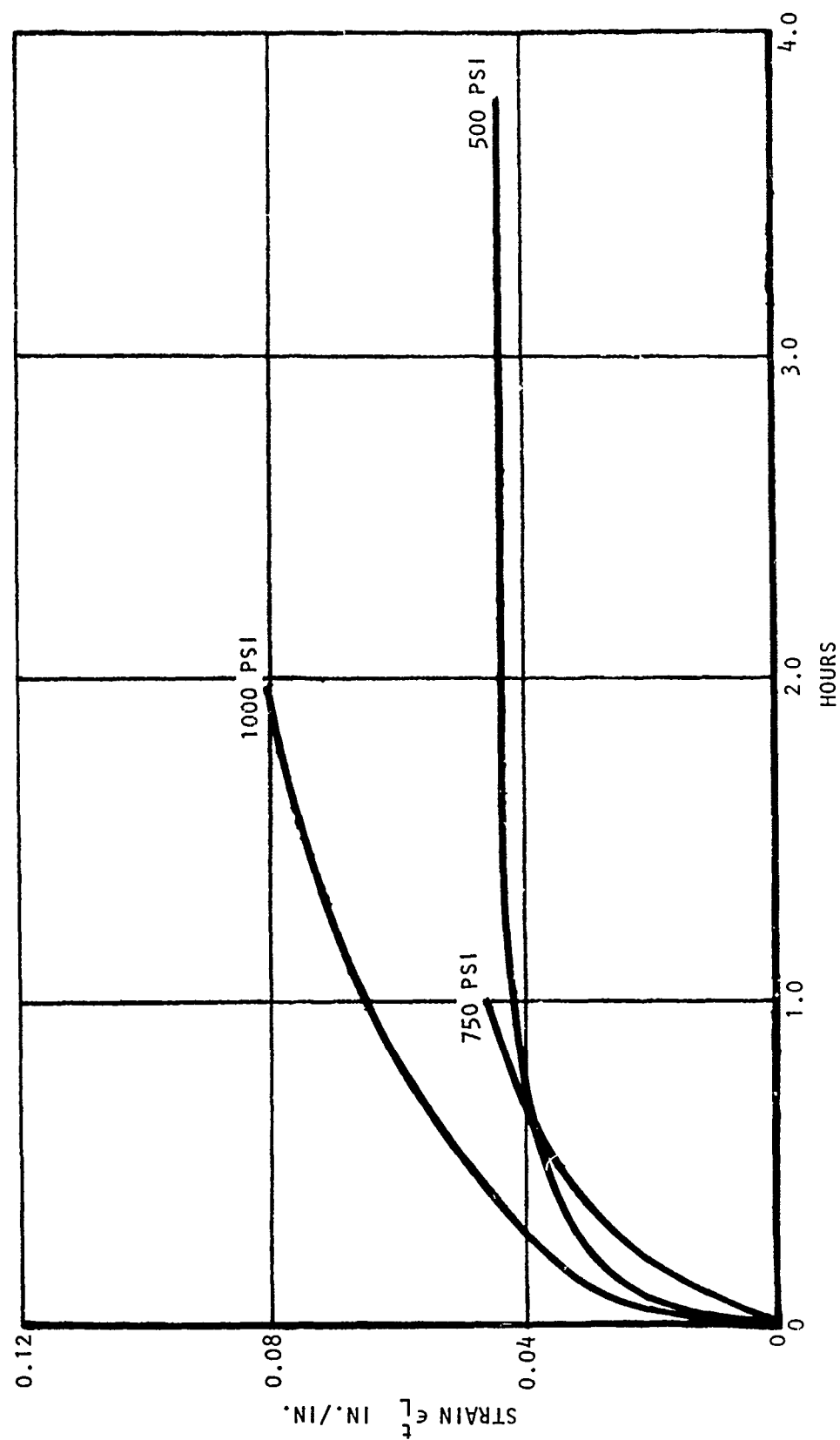


Figure 61. Narmco 2387 Resin Axial Tensile Creep at 350° F

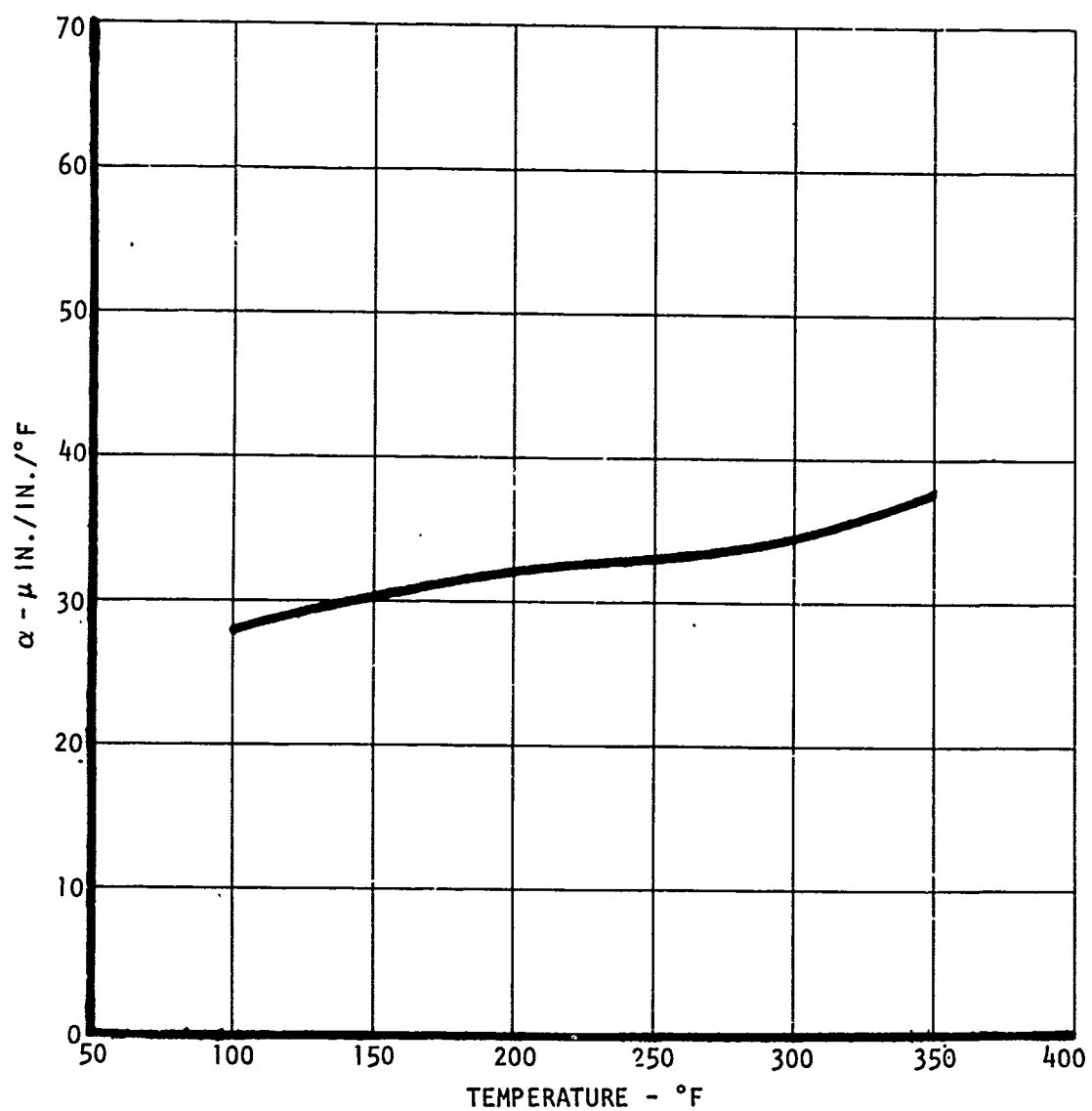


Figure 62. Integrated Average Coefficient of Thermal Expansion for Narmco 2387 Over Range Between RT and Indicated Temperature

SCRIM CLOTH

Mechanical and physical properties of the 104 glass fabric scrim cloth laminate made with the Narmco 2387 resin system without filler were determined at room temperature and 350° F, as outlined in the test program of table LX. Specimens were made from a 12-ply laminate panel with ply thickness about 0.001 inch, giving a final laminate thickness of about 0.012. The cure cycle was identical to that used for the boron/epoxy laminates reported. Properties determined included E^C , E^t , F^{tu} , F^{cu} , F^{su} , ν , G , and the associated stress-strain curves at room temperature and 350° F. In addition, the coefficient of thermal expansion limited creep data at 350° F, and room temperature fatigue strength were determined.

Scrim Cloth Tensile Strength

Longitudinal and transverse room temperature and elevated temperature tensile test data for 104 glass scrim cloth and 2387 resin are presented in tables LXI through LXIV and in figures 63 through 68.

The following summary of average ultimate tensile strength and moduli is given for comparison purposes.

Type Allowable	Room Temperature	350° F
F_L^{tu} , ksi (average)	35.95	35.38
F_T^{tu} , ksi (average)	11.59	10.61
E_L^t , Msi (average)	2.88	2.47
E_T^t , Msi (average)	1.59	1.28

Since the results of the first creep specimen indicated this property to be relatively noncritical for design, it was decided to postcure and static test the remaining two creep specimens. Strength of postcured scrim cloth laminates was of special interest since there was evidence that postcuring would increase the strength of Narmco 2387 resin. The two untested creep specimens were therefore postcured for 14 hours at 350° F to insure the attainment of all postcure effects and then statically tested.

TABLE LX. SCRIM CLOTH CHARACTERIZATION TEST PROGRAM

Type	Test	Type *** Laminate	Thickness	Specimen Type and Size	Number of Specimens	Temperature	Strain Gage and Instrumentation Required
Tension	Long.	104 fabric	12 ply	IITRI 1/2 x 9	5	RT	0°, 90°
			12 ply	IITRI 1/2 x 9	3	350° F	strain gages
	Coeff of therm exp	104 fabric	12 ply	IITRI 1/2 x 9	(1*)	RT → 350	0°, 90° strain gages
	Trans	104 fabric	12 ply	IITRI 1 x 9	3 3	RT 350	0°, 90° strain gages
Compression		104 fabric long.	12 ply	2 w x 8 h Sandwich panel 1/8 cell HC ** Edge-loaded	3	RT	0°, 90° strain gages
					3	350° F	
Creep		104 fabric long.	12 ply	IITRI 1/2 x 9	1	350° F	One 0° strain gage per specimen
Fatigue		104 fabric long.	12 ply	IITRI 1/2 x 9	10 R = 0.1 at 10 stress levels	RT	No instrumentation
Shear		104 fabric	12 ply	Slotted picture frame 6 x 6 1/8 Cell HC **	1	PT	One strain gage rosette per specimen
					1	350° F	
Total		-	-	-	33 + (1)*	-	-
<p>* Conducted using one of the transverse tensile specimens</p> <p>** 1/8-5056-0.001 (4.5 lb/ft³) aluminum HC, 1 inch thick</p> <p>*** 104 glass fabric prepreg using 5505 resin without filler (≈0.001 thickness/ply)</p>							

TABLE LXI. FILAMENTARY LAMINATE STATIC PROPERTY DATA

Material System: 104 Class Fabric/Epoxy Lam Orient: [0/90] Woven
 Type Loading: Tension ☒, Comp ☐, Shear ☐, Interlam Shear ☐
 Type Test Specimen: Coupon, 1/2 x 9 inches with 1-1/2 tabs
 Soak at Temp - °F for - Hr. Test Temp RT °F

Property		Batch No.						
		Spec Ident	1	2	3 (2)			Ave.
Stress (Ksi)	F _{P1}		21.2	21.8	21.0			21.3
	F _{.85}							
	F _{.70}							
	F at 2/3 ϵ_1^{ult}		24.7	25.7	22.4			24.2
	F _{ult}		36.7	37.8	33.3			35.9
Modulus E, Gx10 ⁻⁶	E or G (primary)		2.7	2.7	3.2			2.8
	E' or G' (secondary)		2.1	2.3	2.8			2.4
Strain in./in.	Proportional Limit	ϵ_1	.00780	.00820	.00580			.00726
		ϵ_2			.000960			.000960
		ϵ_{45}						
	Ultimate	ϵ_1	.01380	.01480	.01100			.01320
		ϵ_2			.001230			.001230
		ϵ_{45}						
No. of Plies <u>12</u> Actual Laminate Thickness <u>.0110 to .0117</u> Spec Laminate Thickness: Max <u>-</u> , Min <u>-</u> , Nominal <u>.012</u> Properties based on: Nominal Thickness X ; Actual Thickness								
Filament Count <u>-</u> /in. Void Content <u>-</u> % Ply Thick. <u>-</u> in. Fil Vol Fract <u>0.</u> Resin Wt Fract <u>0.</u> Lam Density <u>-</u> lb/in. ³								
Matrix Desig. <u>Narmco 2387 without filler material</u> Scrim Cloth <u>-</u> Additives Used <u>-</u> Cure Spec <u>-</u>								

Comments: (2) Strain-gaged

TABLE LXII. FILAMENTARY LAMINATE STATIC PROPERTY DATA

Material System: 104 Glass Fabric/Epoxy Lam Orient: [0/90] Woven
 Type Loading: Tension ☒, Comp ☐, Shear ☐, Interlam Shear ☐
 Type Test Specimen: Coupon, 1/2 x 9 in. with 1-1/2 in. Tabs
 Soak at Temp 350 °F for 0.17 Hr. Test Temp 350 °F

Property		Batch No.						
		Spec Ident	1	2	3 (2)			Ave.
Stress (ksi)	FP1		-	13.0	-			-
	F _{.85}		-	-	-			-
	F _{.70}		-	-	-			-
	F at 2/3 ϵ_1^{ult}		28.7	18.9	25.0			24.2
	F _{ult}		43.2	26.0	36.7			35.3
Modulus E, G x 10 ⁻⁶	E or G (primary)		2.00	2.34	2.95			2.47
	E' or G' (secondary)		-	1.875	-			-
Strain in./in.	Proportional Limit	ϵ_1		-	.00410	-		-
		ϵ_2		-	-	-		-
		ϵ_{45}		-	-	-		-
	Ultimate	ϵ_1		.0201	.0095	.0138		.0145
		ϵ_2		-	-	.00121		-
		ϵ_{45}		-	-	-		-
No. of Plies <u>12</u> Actual Laminate Thickness <u>0.0110</u> Spec Laminate Thickness: Max <u>-</u> , Min <u>-</u> , Nominal <u>.012</u> Properties based on: Nominal Thickness χ ; Actual Thickness								
Filament Count <u>-</u> /in. Void Content <u>-</u> % Ply Thick. <u>-</u> in. Fil Vol Fract <u>0.</u> Resin Wt Fract <u>0.</u> Lam Density <u>-</u> lb/in. ³								
Matrix Desig. Narmco <u>2387</u> without filler. <u>-</u> Scrim Cloth <u>-</u> Additives Used <u>-</u> Cure Spec <u>-</u>								

Comments: (2) Strain-gaged

TABLE LXIII. FILAMENTARY LAMINATE STATIC PROPERTY DATA

Material System: 104 Glass Fabric/Epoxy Lam Orient: [0/90] Woven
 Type Loading. Tension ☒, Comp ☐, Shear ☐, Interlam Shear ☐
 Type Test Specimen: Coupon, 1 x 9 in. with 1-1/2 in. tabs
 Soak at Temp - °F for - Hr. Test Temp RT °F

Property		Batch No.	1	2	3 (2)		Ave.
Stress (Ksi)	F _{P1}		7.35	7.20	9.00		7.85
	F _{.85}		-	-	-		-
	F _{.70}		-	-	-		-
	F at 2/3 ϵ_1^{ult}		7.40	7.55	9.1		8.01
	F _{ult}		10.58	10.77	13.41		11.59
Modulus E, Gx10 ⁻⁶	E or G (primary)		1.54	1.68	1.54		1.59
	E' or G' (secondary)		-	1.26	1.25		-
Strain in./in.	Proportional Limit	ϵ_1	.00525	.00470	.00555		.00517
		ϵ_2	-	-	.000600		-
		ϵ_{45}	-	-	-		-
	Ultimate	ϵ_1	.00750	.00750	.00837		.00779
		ϵ_2	-	-	.000810		-
		ϵ_{45}	-	-	-		-
No. of Plies <u>12</u> Actual Laminate Thickness <u>.0110-.0115</u> inch Spec Laminate Thickness: Max <u>-</u> , Min <u>-</u> , Nominal <u>.012</u> Properties based on: Nominal Thickness x ; Actual Thickness							
Filament Count <u>-</u> /in. Void Content <u>-</u> % Ply Thick. <u>-</u> in. Fil Vol Fract <u>0.</u> Resin Wt Fract <u>0.</u> Lam Density <u>-</u> lb/in. ³							
Matrix Desig. <u>Narmco 2387 without filler.</u> Scrim Cloth <u>-</u> Additives Used <u>-</u> Cure Spec <u>-</u>							

Comments: (2) Strain-gaged

TABLE LXIV. FILAMENTARY LAMINATE STATIC PROPERTY DATA

Material System: 104 Glass Fabric/Epoxy Lam Orient: [0/90] Woven
 Type Loading: Tension ☒, Comp ☐, Shear ☐, Interlam Shear ☐
 Type Test Specimen: Coupon, 1 x 9 in. with 1-1/2 in. Tabs
 Soak at Temp 350 °F for .17 Hr. Test Temp 350 °F

Property		Batch No.	Spec Ident	1	2	3 (2)			Ave.
Stress (Ksi)	F _{P1}			4.20	4.25	4.55			4.33
	F _{.85}			8.20	-	-			-
	F _{.70}			-	-	-			-
	F at 2/3 ϵ_1^{ult}			6.25	7.80	8.20			7.42
	F _{ult}			8.66	11.44	11.73			10.61
Modulus E, Gx10 ⁻⁶	E or G (primary)			1.17	1.16	1.51			1.28
	E' or G' (secondary)			1.09	.99	1.23			1.10
Strain in./in.	Proportional Limit	ϵ_1		.00390	.00370	.00315			.00354
		ϵ_2		-	-	.000320			-
		ϵ_{45}		-	-	-			-
	Ultimate	ϵ_1		.00900	.01065	.00932			.00966
		ϵ_2		-	-	.00069			-
		ϵ_{45}		-	-	-			-
No. of Plies <u>12</u> Actual Laminate Thickness <u>0.0110</u> Spec Laminate Thickness: Max <u>-</u> , Min <u>-</u> , Nominal <u>.012</u> Properties based on: Nominal Thickness <u>X</u> ; Actual Thickness <u>-</u>									
Filament Count <u>-</u> /in. Void Content <u>-</u> % Ply Thick. <u>-</u> in. Fil Vol Fract <u>0.</u> Resin Wt Fract <u>0.</u> Lam Density <u>-</u> lb/in. ³									
Matrix Desig. <u>Narmco 2387 without filler.</u> Scrim Cloth <u>-</u> Additives Used <u>-</u> Cure Spec <u>-</u>									

Comments: (2) Strain-gaged

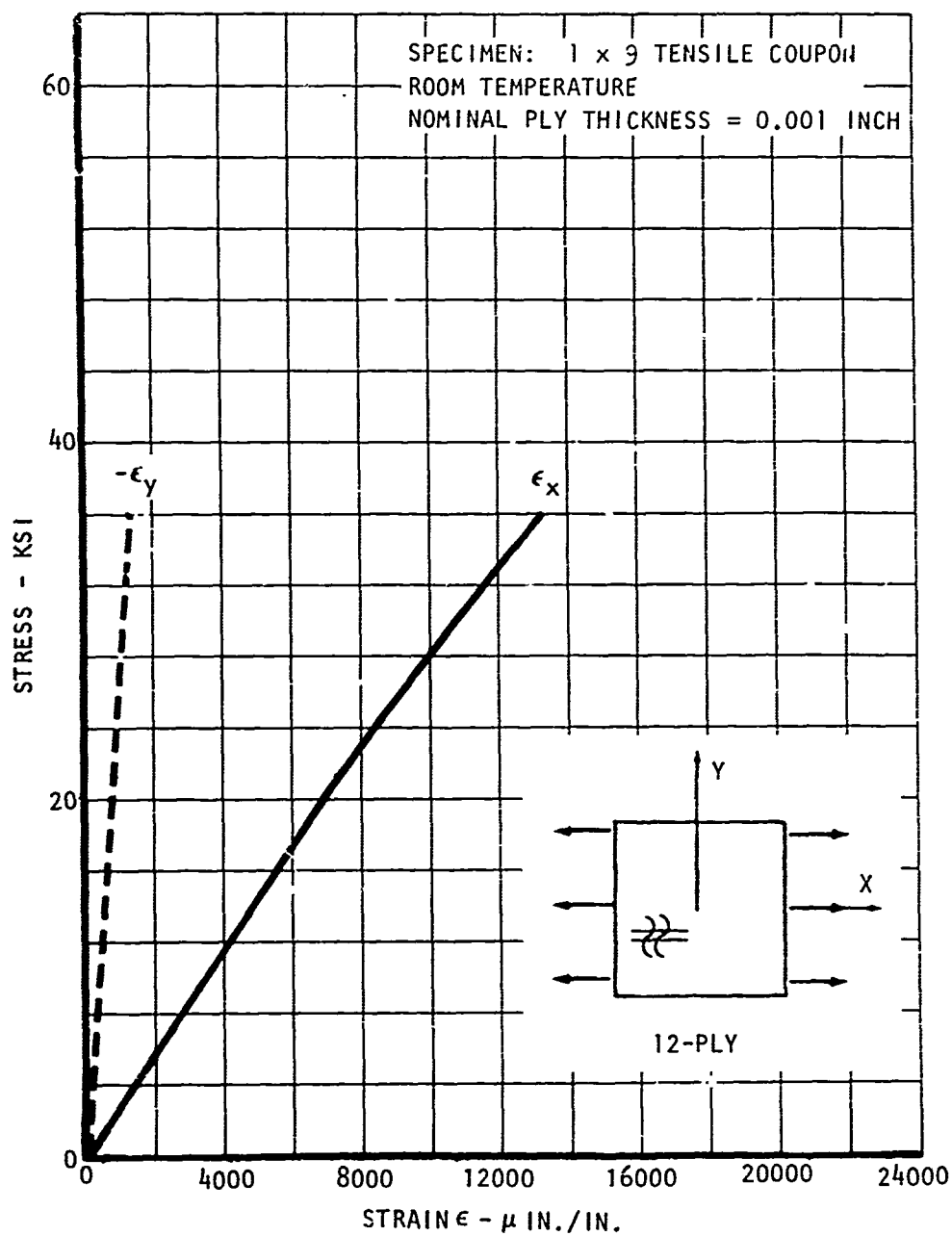


Figure 63. Longitudinal Tension Stress-Strain
Curves - 104 Glass Scrim Cloth - RT

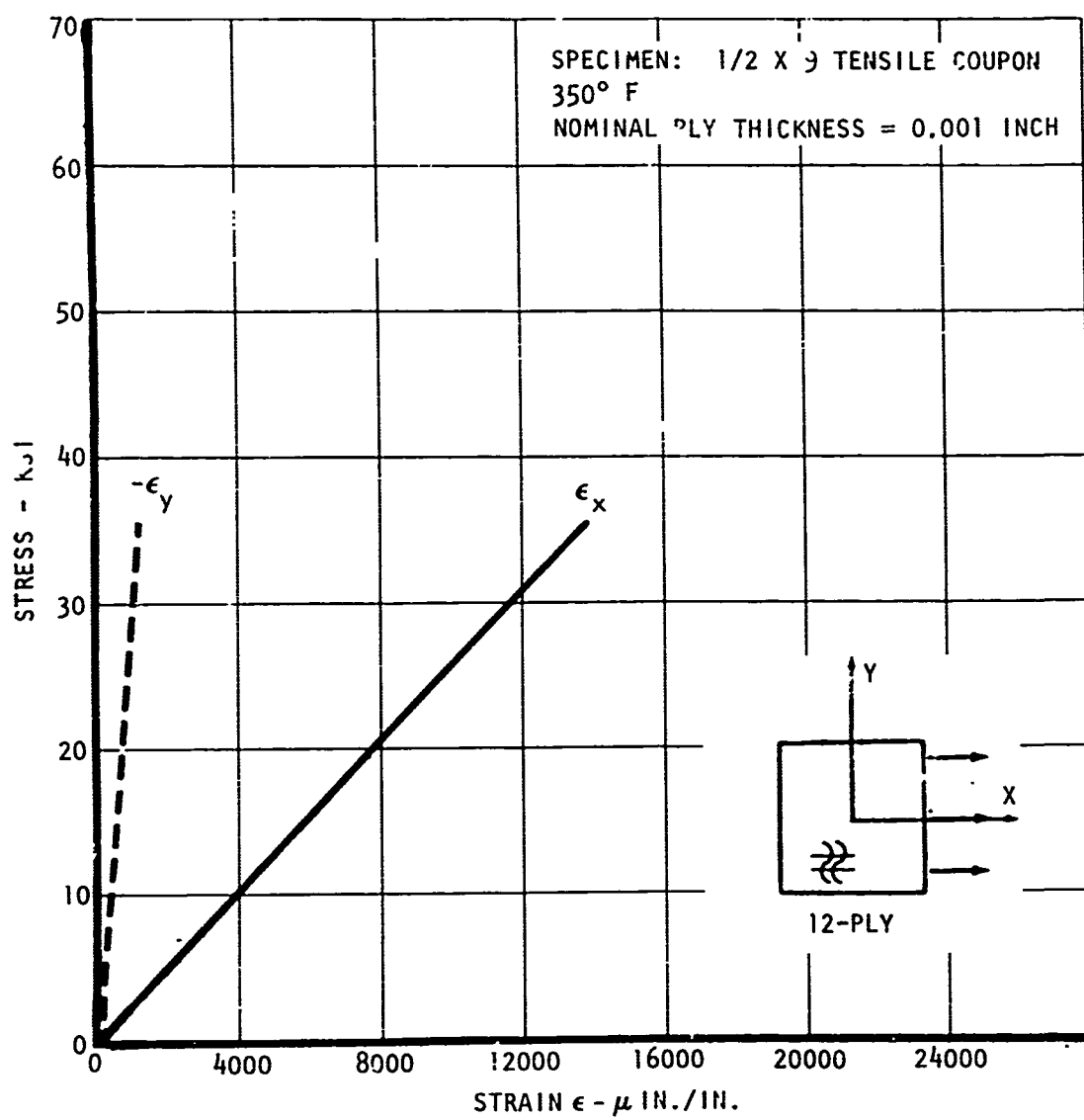


Figure 64. Longitudinal Tension Stress-Strain
Curves - 104 Glass Scrim Cloth -350° F

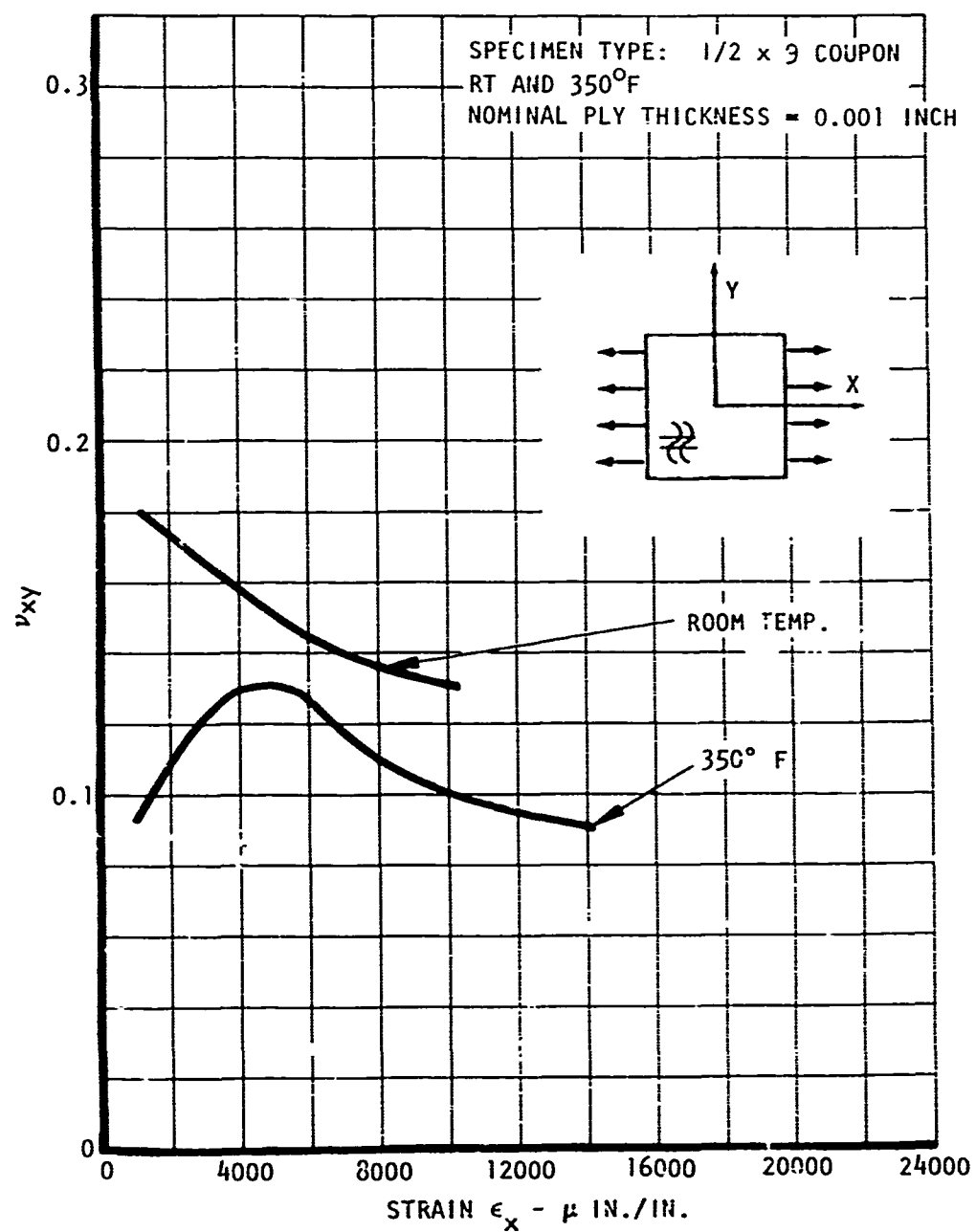


Figure 65. Poisson's Ratio ν_{xy} vs ϵ_x - 104 Glass Scrim Cloth

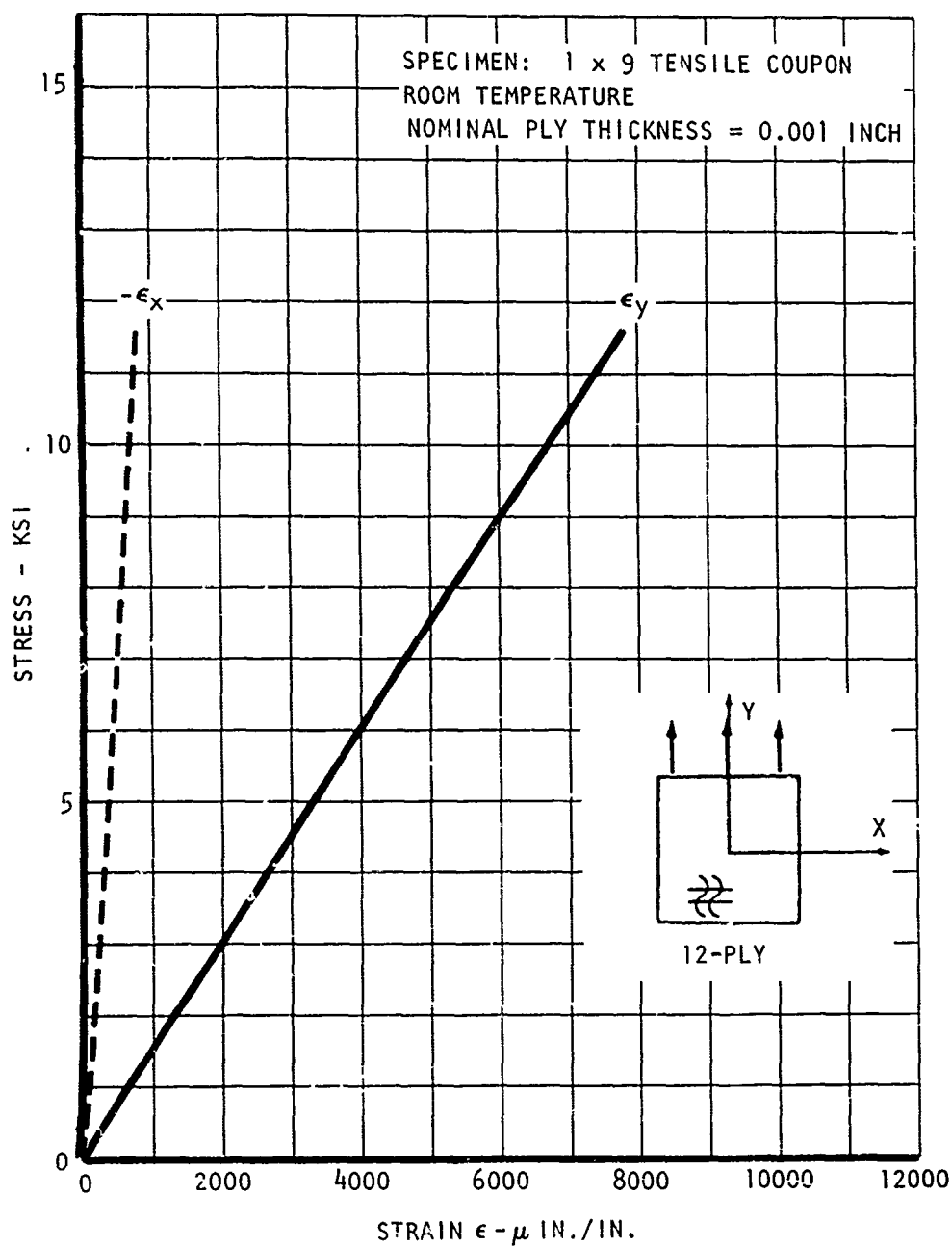


Figure 66. Transverse Tension Stress-Strain Curve - 104 Glass Scrim Cloth -RT

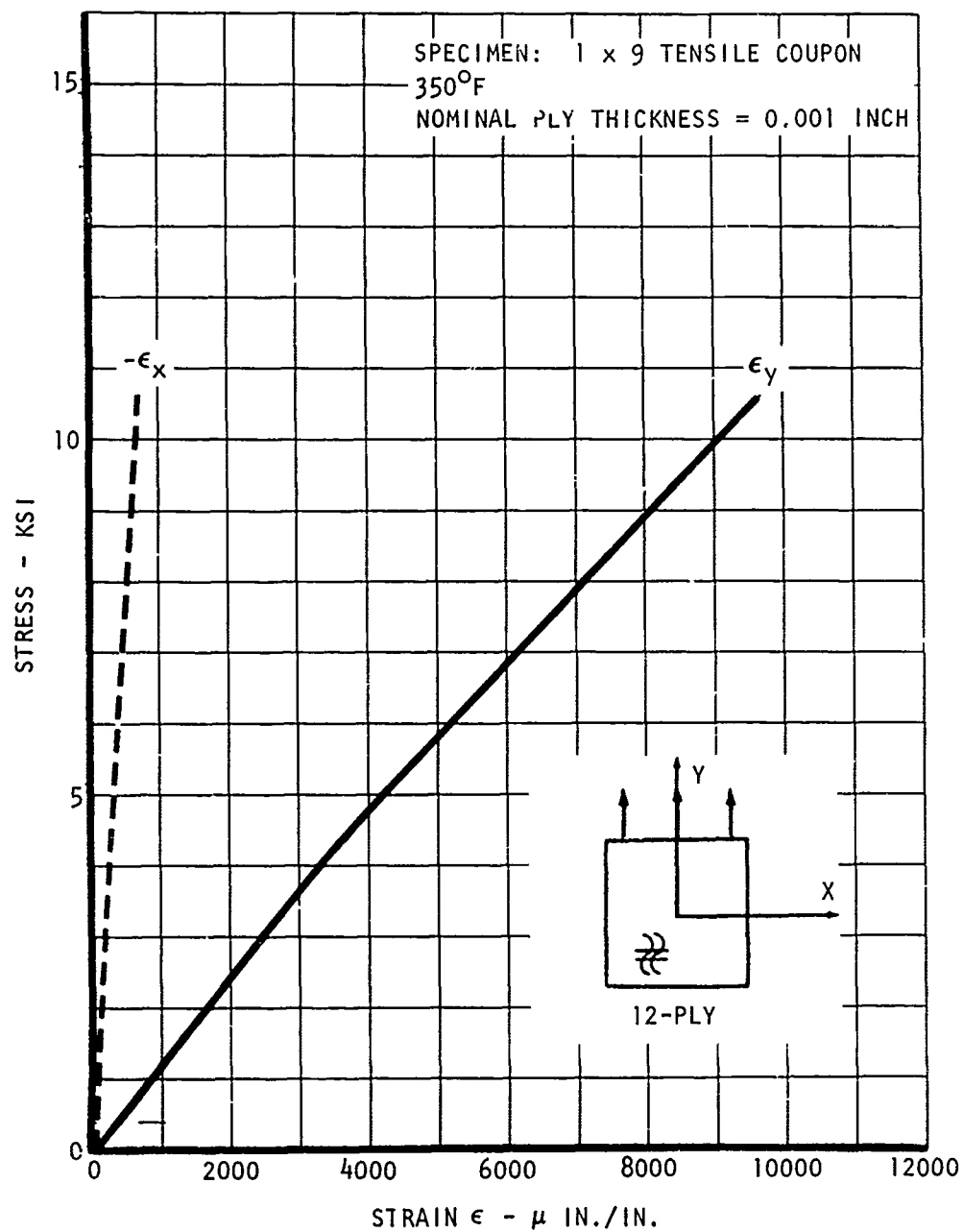


Figure 67. Transverse Tension Stress-Strain Curve -
104 Glass Scrim Cloth - 350° F

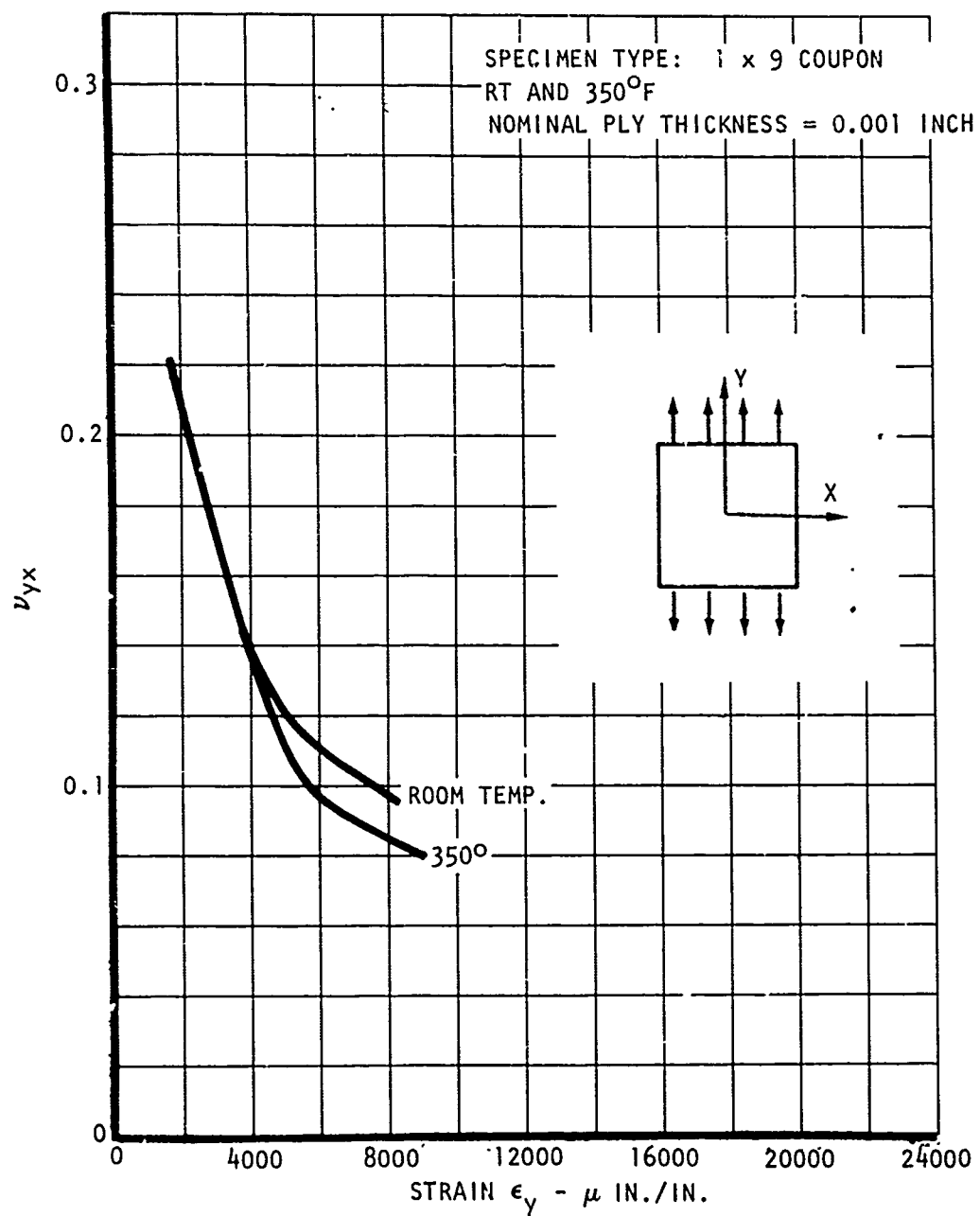


Figure 68. Poisson's Ratio ν_{yx} vs ϵ_y - 104 Glass Scrim Cloth

Results of the postcured scrim cloth specimens are listed in table LXV and plotted in figures 69 and 70. Comparison of these data with earlier tests of specimens without postcure indicates that there is relatively little difference in room temperature properties, as noted in the following tabulation:

<u>Property</u>	<u>Non-Postcured Specimens</u>	<u>Postcured Specimens</u>
Proportional limit, F^{tp1}	21.3 ksi	23.4 ksi
Ultimate stress, F^{tu}	35.9 ksi	39.3 ksi
Modulus, E_x	2.88 Msi	2.90 Msi
Ultimate strain, ϵ^{tu}	0.0132 in./in.	.015 in./in.
Poisson's ratio, ν -		
At strain 0.004 in/in	0.150	0.143
At strain 0.010 in/in	0.124	0.126
At strain 0.018 in/in	-	0.093

It can be concluded that postcure of the Narmco 2387 resin has no significant influence on the longitudinal properties of the scrim laminates at room temperature.

Scrim Cloth Compression Strength

Room temperature compression properties of the 12-ply, 104 glass fabric laminates, tested as faces of a 1-inch-thick aluminum honeycomb sandwich specimen, are given in table LXVI and figure 71. Types of failure are shown in the photograph (figure 72). Failure occurred by a compressive fracture of the face sheet in a line across the specimen followed by an overlapping of the failed ends. In two instances, both faces failed simultaneously; in the other, only one face failed, resulting in a curved specimen shape.

Elevated temperature results are given in table LXVII and figure 73. The type of failure, shown in figure 74, was of a single face in all instances. Fracture was similar in appearance to the room temperature specimens.

Poisson's ratio results are shown for room and elevated temperature in figure 75.

TABLE LXV. FILAMENTARY LAMINATE STATIC PROPERTY DATA

Material System: 104 Glass Fabric/Epoxy Lam Orient: [0/90] Woven
 Type Loading: Tension ☒, Comp ☐, Shear ☐, Interlam Shear ☐
 Type Test Specimen: Coupon, 1/2 x 9 in. with 1-1/2 in. tabs
 Soak at Temp - °F for - Hr. Test Temp RT °F

Property		Batch No. (1)						
		Spec Ident	1	2				Ave.
Stress (Ksi)	F _{P1}		23.4	23.4				23.4
	F _{.85}							
	F _{.70}							
	F at 2/3 ϵ_1^{ult}							
	F _{ult}		35.2	43.5	(2)			39.3
Modulus E, G x 10 ⁻⁶	E or G (primary)		2.90	2.90				2.90
	E' or G' (secondary)							
Strain in./in.	Proportional Limit	ϵ_1	.0083	.0085				.0084
		ϵ_2	-.00114	-				-
		ϵ_{45}						
	Ultimate	ϵ_1	.0130	.0169				.0150
		ϵ_2						
		ϵ_{45}						
No. of Plies <u>12</u> Actual Laminate Thickness <u>.0115</u> Spec Laminate Thickness: Max <u>-</u> , Min <u>-</u> , Nominal <u>.012</u> Properties based on: Nominal Thickness x ; Actual Thickness								
Filament Count <u>-</u> /in. Void Content <u>-</u> % Ply Thick. <u>-</u> in. Fil Vol Fract <u>0.</u> Resin Wt Fract <u>0.</u> Lam Density <u>-</u> lb/in. ³								
Laminate: Tape or Matrix Desig <u>2387 resin</u> Manuf <u>Narmco</u> Scrim Cloth <u>-</u> Additives Used <u>No filler</u> Cure Spec <u>-</u>								

Comments: (1) Specimens were postcured for 10 hours at 350° F.
 (2) Both failed at extensometer pin point grip attachment.

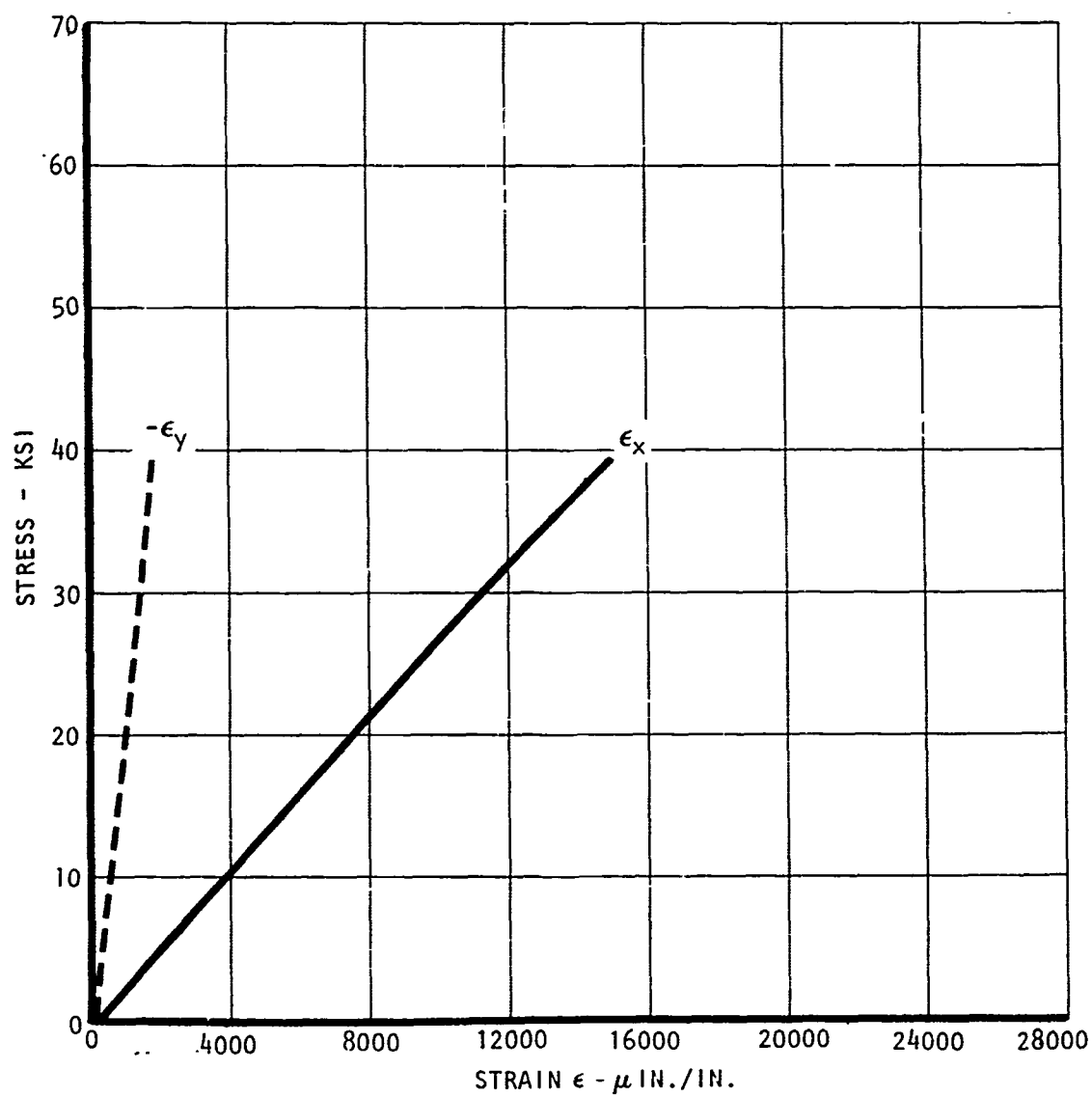


Figure 69. Longitudinal Tension, Postcured Scrim Laminate at RT

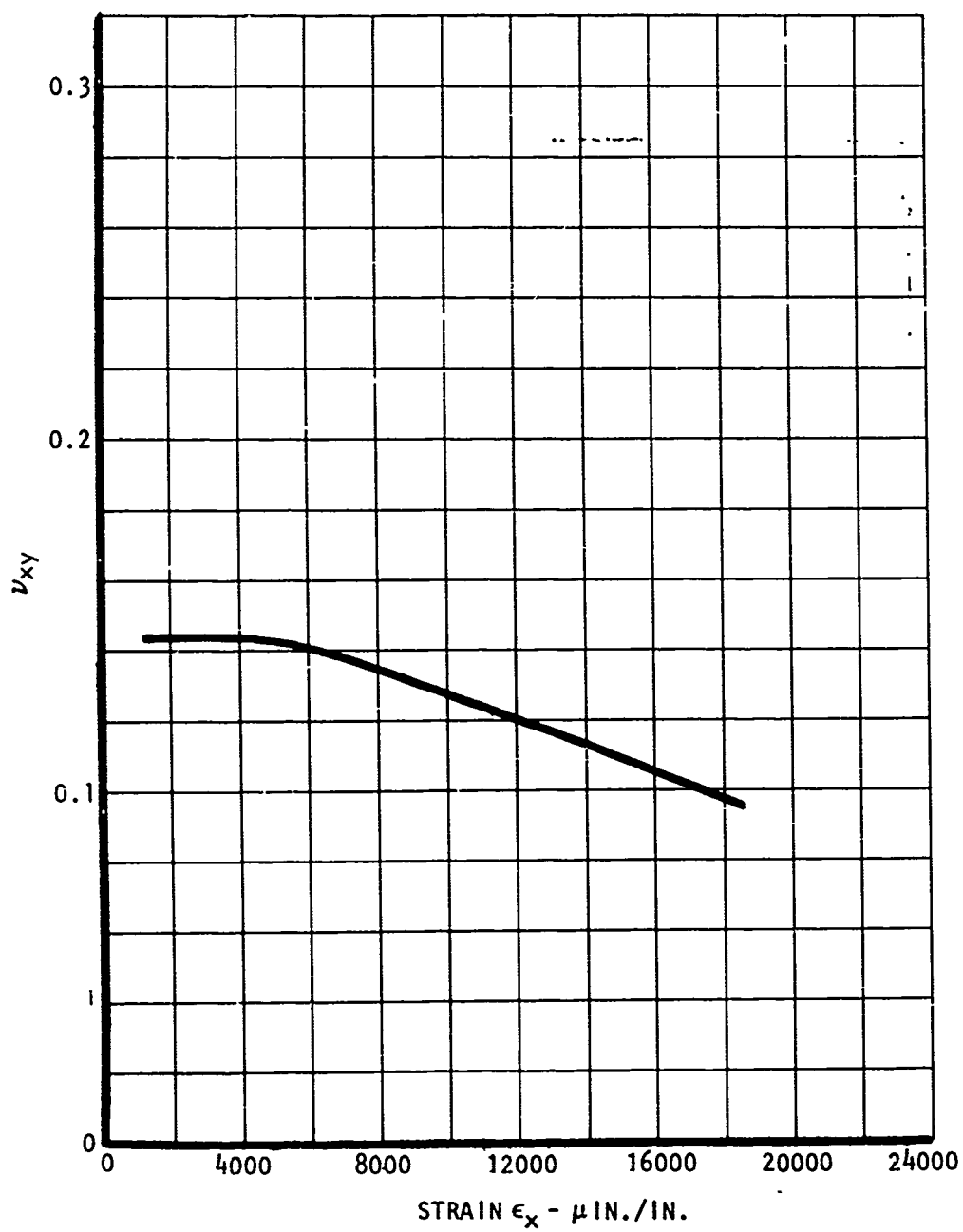


Figure 70. Poisson's Ratio for Postcured Scrim Laminate at Room Temp

TABLE LXVI. FILAMENTARY LAMINATE STATIC PROPERTY DATA

Material System: 104 Glass Fabric/Epoxy Lam Orient: [0/90] Woven
 Type Loading: Tension ☐, Comp ☒, Shear ☐, Interlam Shear ☐
 Type Test Specimen: Honeycomb Sandwich Edgewise Compression Specimen
 Soak at Temp - °F for - Hr. Test Temp RT °F

Property		Batch No. Spec Ident	1	2	3 (2)			Ave.
Stress (Ksi)	ϵ_{p1}		-9.15	-9.61	-8.87			-9.21
	$F_{.85}$		-	-	-			-
	$F_{.70}$		-	-	-			-
	F at $2/3 \epsilon_1^{ult}$		-16.6	-16.8	-16.8			-16.7
	F^{ult}		-46.8	-47.9	-45.3			-46.7
Modulus $E, G \times 10^{-6}$	E or G (primary)		4.57	4.80	4.68			4.68
	E' or G' (secondary)		3.04	3.21	-			3.12
Strain in./in.	Proportional Limit	ϵ_1	.00200	.00200	.00180			.00195
		ϵ_2	-	-	.000550			.000550
		ϵ_{45}	-	-	-			-
	Ultimate	ϵ_1	.01190	.01230	.01190			.01203
		ϵ_2	-	-	.00310			.00310
		ϵ_{45}	-	-	-			-
No. of Plies <u>12</u> Actual Laminate Thickness _____ Spec Laminate Thickness: Max _____, Min _____, Nominal <u>.012</u> Properties based on: Nominal Thickness x ; Actual Thickness _____								
Filament Count _____/in. Void Content _____ % Ply Thick. _____ in. Fil Vol Fract <u>0.</u> Resin Wt Fract <u>0.</u> Lam Density _____ lb/in. ³								
Laminate: Tape or Matrix Desig <u>2387 resin</u> Manuf <u>Narmco</u> Scrim Cloth _____ Additives Used <u>No filler</u> Cure Spec _____								

Comments: (2) Strain-gaged

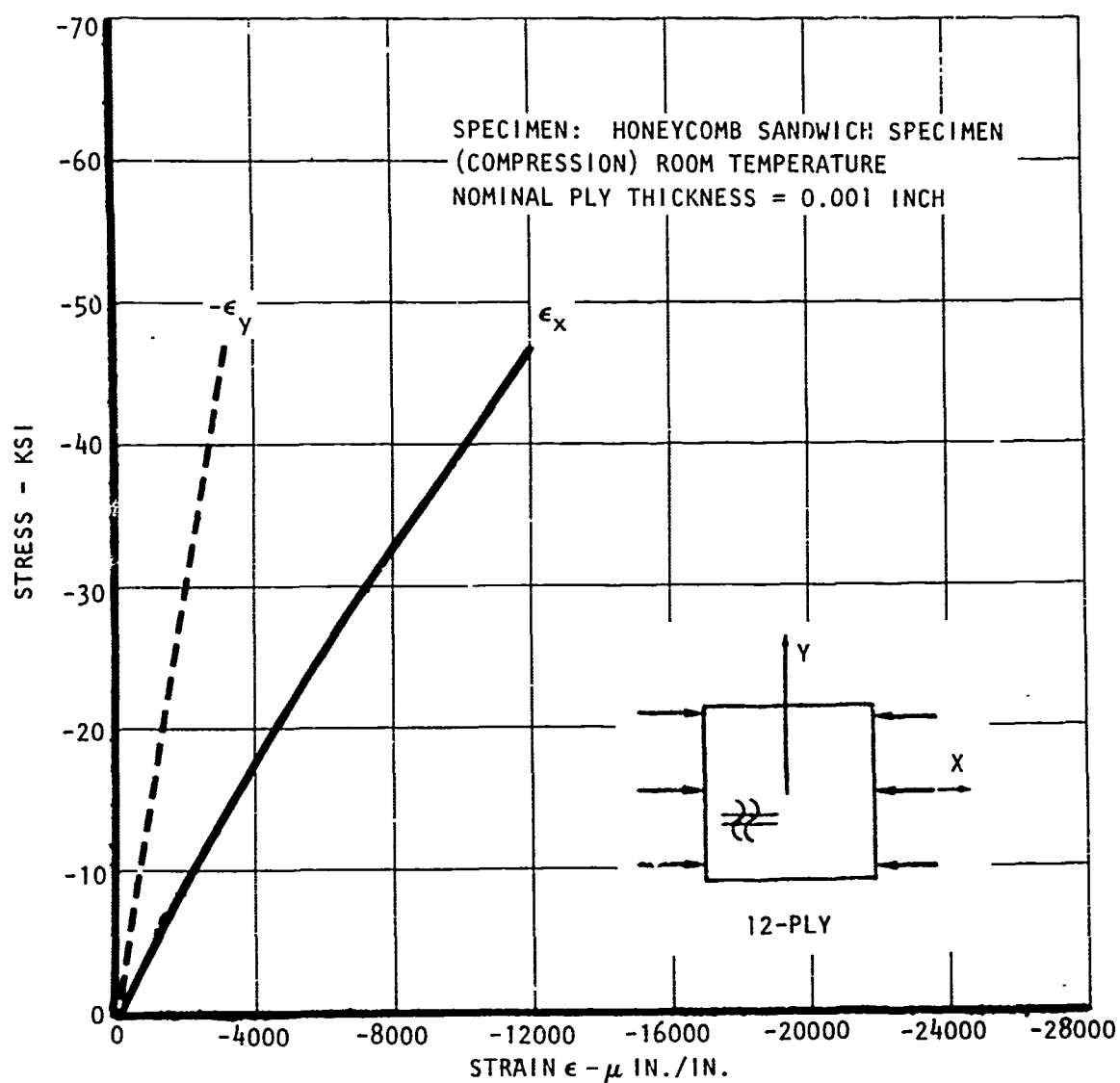
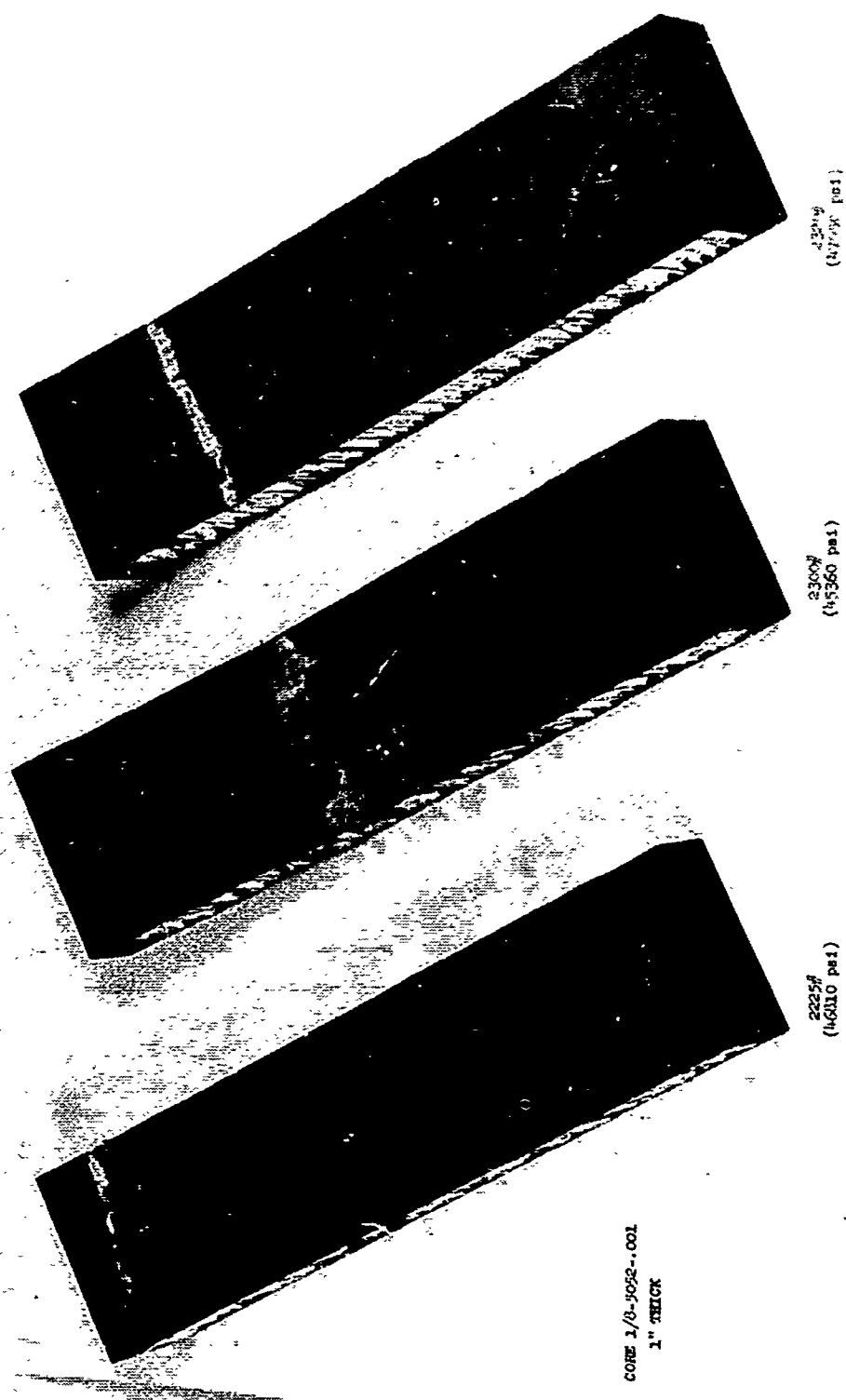


Figure 71. Longitudinal Compression - 104 Glass Scrim Cloth - RT



FAILURE OF 12 PLY 104 FABRIC FACED COMPRESSION SPECIMENS TESTED AT ROOM TEMPERATURE

Figure 72. Scrim Cloth Compression Specimens After Failure at Room Temperature

TABLE LXVII. FILAMENTARY LAMINATE STATIC PROPERTY DATA

Material System: 104 Glass Fabric/Epoxy Lam Orient: [0/90] Woven
 Type Loading: Tension ☐, Comp ☒, Shear ☐, Interlam Shear ☐
 Type Test Specimen: Honeycomb Sandwich Edgewise Compression Specimen
 Soak at Temp 350 °F for 0.17 Hr. Test Temp 350 °F

Property		Batch No.	Spec Ident	4	5	6 (2)		Ave.
Stress (Ksi)	F _{P1}			-7.14	-8.72	-8.40		-8.09
	F _{.85}			-	-	-		-
	F _{.70}			-	-	-		-
	F at 2/3 ϵ_1^{ult}			-20.0	-21.2	-20.5		-20.7
	F _{ult}			-29.3	-30.6	-29.3		-29.7
Modulus E, Gx10 ⁻⁶	E or G (primary)			4.12	3.98	4.68		4.26
	E' or G' (secondary)			3.09	3.11	3.25		3.11
Strain in./in.	Proportional Limit	ϵ_1		-.00174	-.00225	-.00220		-.00210
		ϵ_2		-	-	+.0004		+.0004
		ϵ_{45}		-	-	-		-
	Ultimate	ϵ_1		.00726	.00875	-.00838		.00813
		ϵ_2		-	-	+.00145		+.00145
		ϵ_{45}		-	-	-		-
No. of Plies <u>12</u> Actual Laminate Thickness _____ Spec Laminate Thickness: Max _____, Min _____, Nominal <u>.012</u> Properties based on: Nominal Thickness x ; Actual Thickness								
Filament Count _____ /in. Void Content _____ % Ply Thick. _____ in. Fil Vol Fract <u>0.</u> Resin Wt Fract <u>0.</u> Lam Density _____ lb/in. ³								
Laminate: Tape or Matrix Desig <u>2387 resin</u> Manuf <u>Narmco</u> Scrim Cloth _____ Additives Used <u>No filler</u> Cure Spec _____								

Comments: (2) Strain-gaged

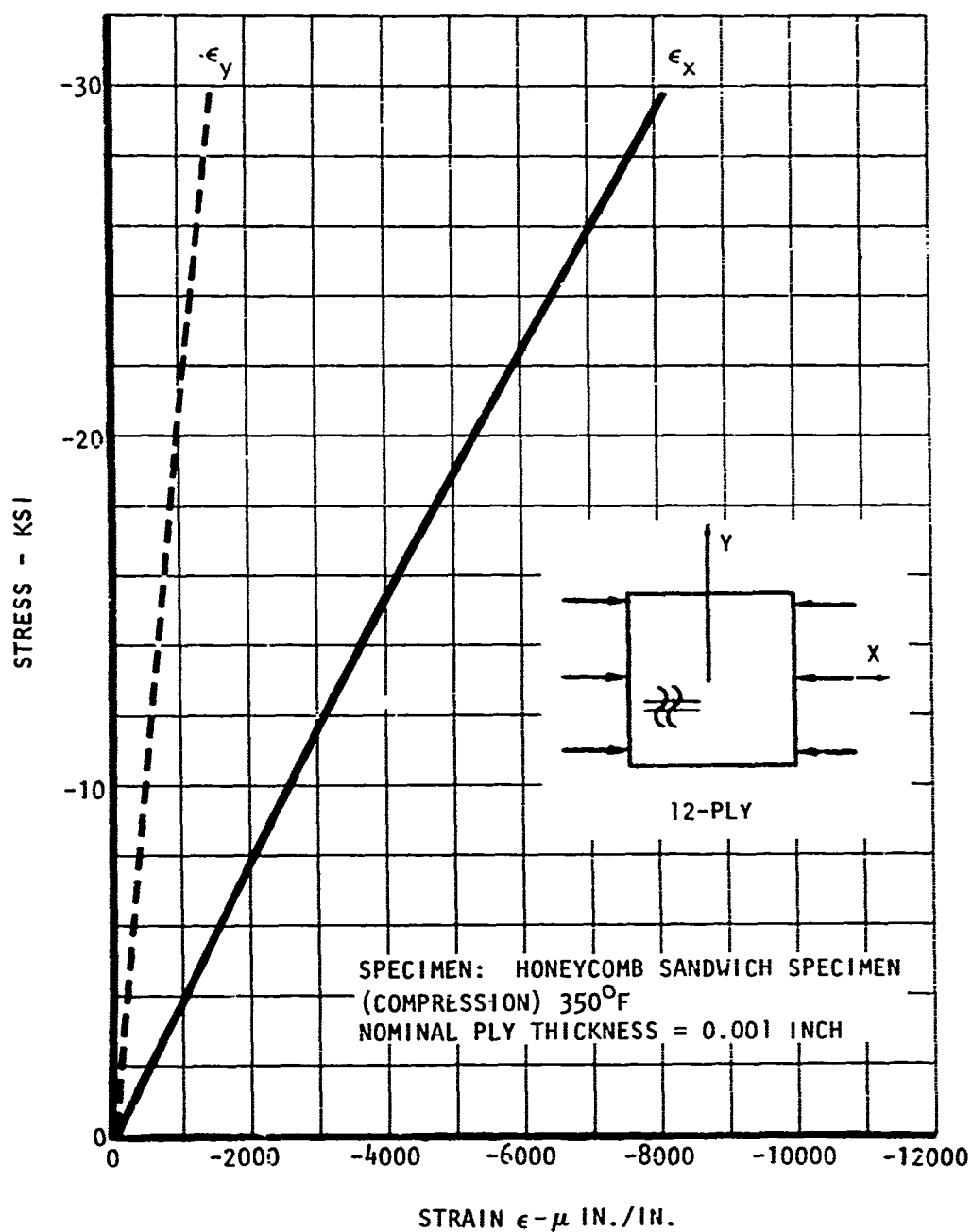
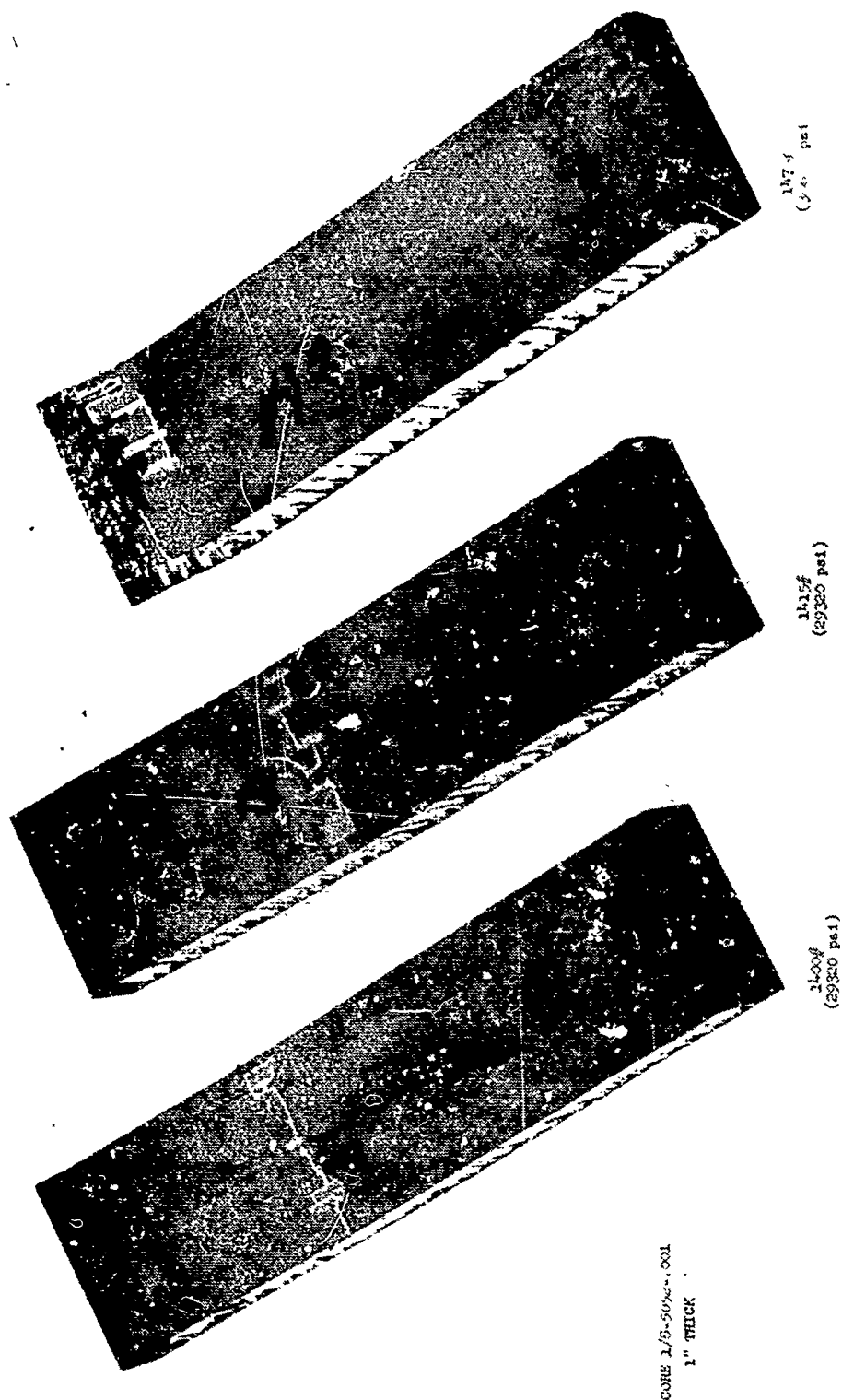


Figure 73. Longitudinal Compression - 104 Glass Scrim Cloth - 350°F



FAILURE OF 12 PLY 104 FABRIC FACED COMPRESSION SPECIMENS TESTED AT 350°F

Figure 74. Failure of 12-Ply 104-Glass Fabric Compression Specimens Tested at 350°F

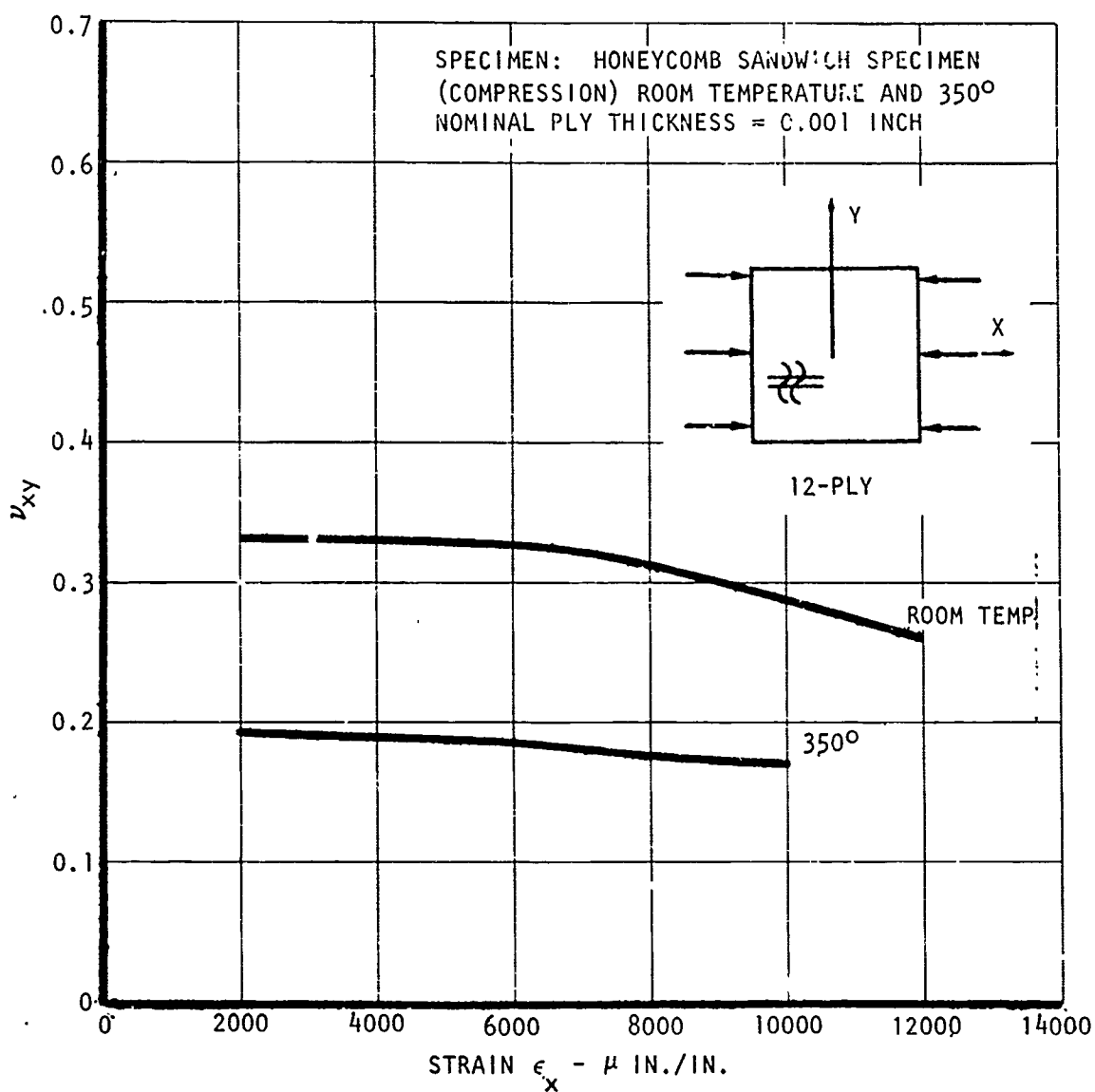


Figure 75. Poisson's Ratio ν_{xy} vs ϵ_x - 104 Glass Scrim Cloth

Scrim Cloth Shear Strength

In-plane shear tests at room temperature and 350° F were conducted on sandwich panel specimens having 12-ply, 104 scrim cloth laminate faces and 1/8-5052-0.001 aluminum honeycomb core. Specimens were instrumented with strain gage rosettes (EA-06-250RA-120, Micro-Measurements), one on each face of the honeycomb panel. (See sketch, figure 79.) The center leg (No. 2) of each rosette was parallel to the edge of the test section, thus coincident with the axis of the applied shear. The other legs (No. 1 and No. 3) were at +45° and -45° to the shear axis. Under this condition, pure shear will produce equal strains of opposite sign in gages No. 1 and No. 3, and a zero reading in gage No. 2. This condition was closely approximated by the recorded strain gage readings on both specimens, as indicated in the following tabulation:

Specimen	Load % Ultimate	Temperature	Rosette Location	Strain Gage Reading - $\mu\text{in./in.}$		
				Gage Rotation Relative to Shear Axis		
				+45°	0°	-45°
1	93	RT	Side 1	10,962	1,381	-9,852
			Side 2	9,805	60	-10,003
2	92	350° F	Side 1	22,220	312	-22,490
			Side 2	20,610	711	-21,650

In only one instance did the center gage reading represent a significant percentage of the diagonal readings. The surface ply of this face did not maintain true orthotropy but appeared to be off 90 degrees between warp and fill directions.

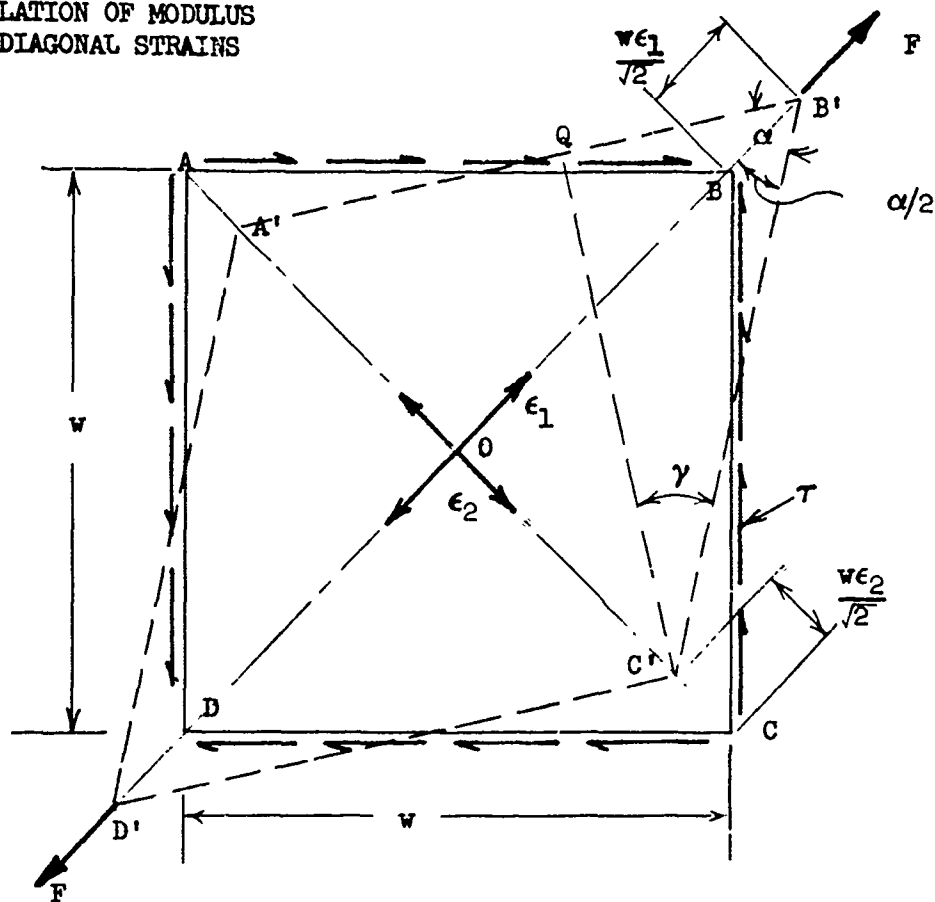
Shear strain and shear modulus were obtained from the +45° and -45° strain readings using the method shown in figure 76.

Room temperature strain gage readings are plotted versus applied shear stress in figure 77. These show the consistency of the recorded data and the nonlinearity of the shear response.

Results of the room temperature test are tabulated in the data sheet (table LXIII) and plotted as shear stress versus shear strain in figure 78. The specimen after failure is shown in figure 79.

Elevated temperature shear data have been processed in a similar manner. However, in this case, an estimated correction had to be made for the creep which was experienced, especially at the higher stress levels. From the record of machine head deflection, a composite loading curve was constructed by joining the segments representing the increase from each load level to the next. This eliminates the creep occurring during the reading periods and the

CALCULATION OF MODULUS
FROM DIAGONAL STRAINS



$$\tan \alpha/2 = OC'/OB' = \frac{(w/\sqrt{2}) + (w\epsilon_2/\sqrt{2})}{(w/\sqrt{2}) + (w\epsilon_1/\sqrt{2})} = \frac{1 + \epsilon_2}{1 + \epsilon_1}$$

$$\tan \alpha/2 = \sqrt{(1 - \cos \alpha)/(1 + \cos \alpha)} = \sqrt{(1 - \sin \gamma)/(1 + \sin \gamma)}$$

$$\frac{1 - \sin \gamma}{1 + \sin \gamma} = \left(\frac{1 + \epsilon_2}{1 + \epsilon_1} \right)^2 = \frac{1 + 2\epsilon_2 + \epsilon_2^2}{1 + 2\epsilon_1 + \epsilon_1^2} \quad \begin{array}{l} \text{NEGLECT } \epsilon^2 \\ \text{ASSUME } \sin \gamma = \gamma \end{array}$$

$$\frac{1 - \gamma}{1 + \gamma} = \frac{1 + 2\epsilon_2}{1 + 2\epsilon_1}$$

$$1 + 2\epsilon_1 - \gamma - 2\gamma\epsilon_1 = 1 + 2\epsilon_2 + \gamma + 2\gamma\epsilon_2$$

$$\gamma = (\epsilon_1 - \epsilon_2)/(1 + \epsilon_1 + \epsilon_2)$$

$$G = \tau/\gamma = \frac{.707 F}{wt} \frac{1 + \epsilon_1 + \epsilon_2}{\epsilon_1 - \epsilon_2}$$

Figure 76. Calculation of Shear Modulus From Diagonal Strains

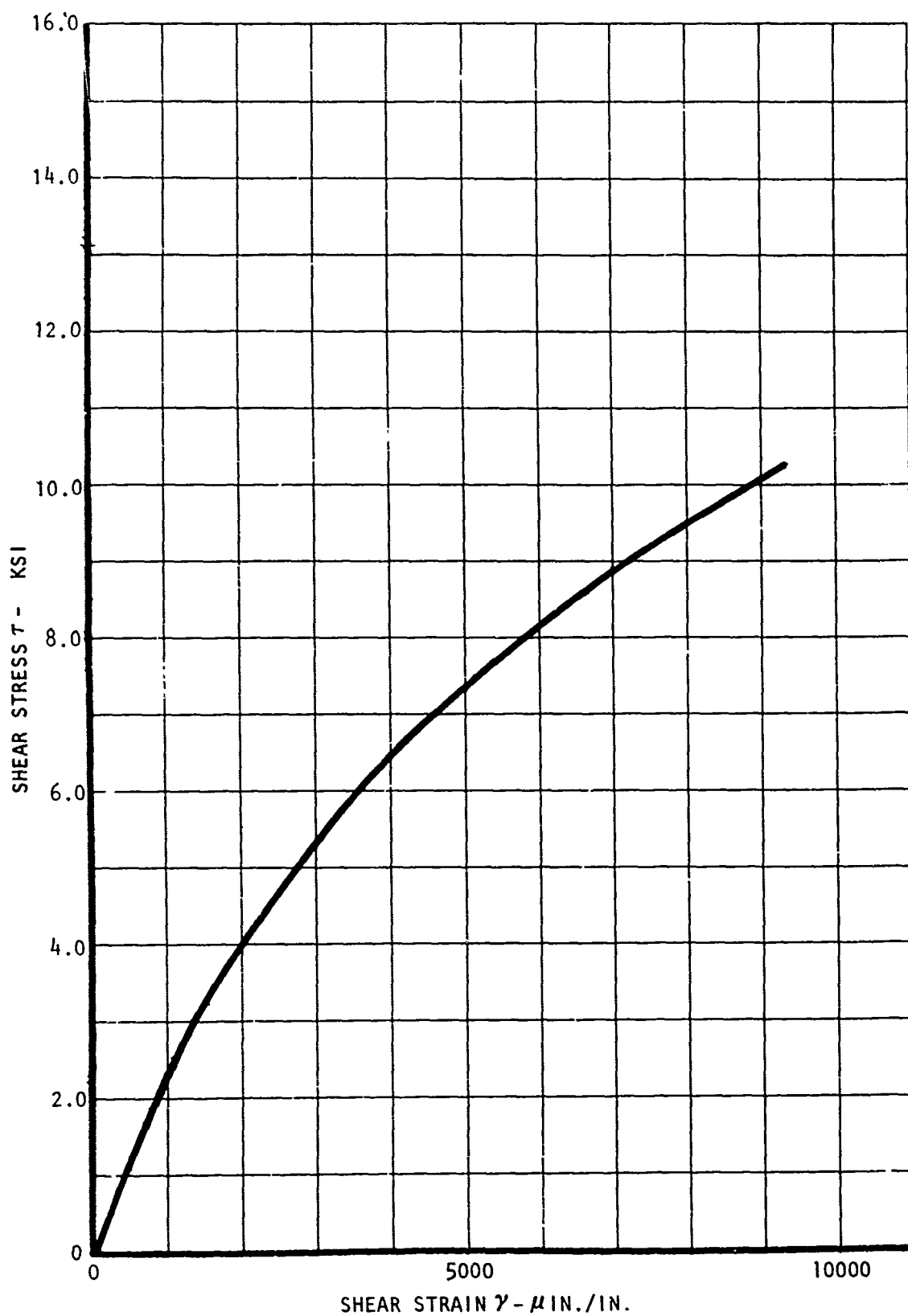


Figure 77. Shear Stress versus Shear Strain - 104 Glass Scrim Cloth - RT

TABLE LXVIII. FILAMENTARY LAMINATE STATIC PROPERTY DATA

Material System: 104 Glass Fabric/Epoxy Lam Orient: [0/90] Woven
 Type Loading: Tension ☐, Comp ☐, Shear ☒, Interlam Shear ☐
 Type Test Specimen: Pure Shear Picture Frame, II/C Sandwich
 Soak at Temp °F for Hr. Test Temp RT °F

Property		Batch No.					
		Spec Ident	(1)				Ave.
Stress (Ksi)	F_{P1}		2.10				2.10
	$F_{.85}$		5.35				5.35
	$F_{.70}$		7.95				7.95
	F at $2/3 \epsilon_1^{ult}$		9.10				9.10
	F_{ult}		11.11				11.11
Modulus $E, G \times 10^{-6}$	E or G (primary)		.93				.93
	E' or G' (secondary)		--				--
Strain in./in.	Proportional Limit	γ	.00230				.00230
			---				---
			---				---
	Ultimate	γ	.0229				.0227
			---				---
			---				---
No. of Plies <u>12/</u> Actual Laminate Thickness <u> </u> Spec Laminate Thickness: Max <u> </u> , Min <u> </u> , Nominal <u>.012</u> Properties based on: Nominal Thickness X ; Actual Thickness <u> </u>							
Filament Count <u> </u> /in. Void Content <u> </u> % Ply Thick. <u> </u> in. Fil Vol Fract <u>0.</u> Resin Wt Fract <u>0.</u> Lam Density <u> </u> lb/in. ³							
Laminate: Tape or Matrix Desig <u>2387 resin</u> Manuf. <u>Narmco</u> Scrim Cloth <u> </u> Additives Used <u>No filler</u> Cure Spec <u> </u>							

Comments: (1) Strain-gaged

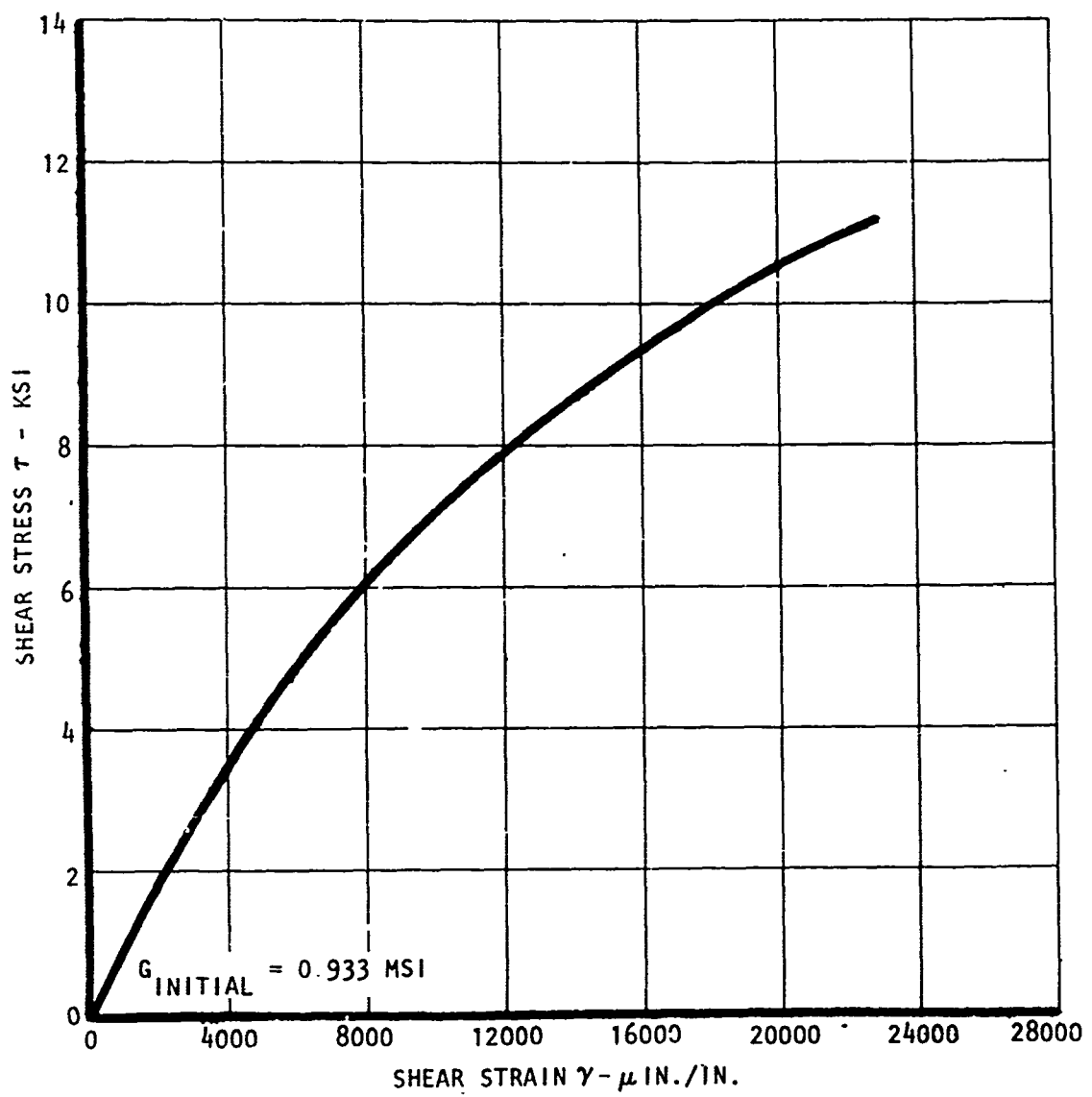


Figure 78. Shear Stress versus Shear Strain - 104 Glass Scrim Cloth - RT

loading dropbacks. By applying the same percentage of loading deflection versus total deformation to the strain gage readings, a corrected plot of diagonal strain versus shear stress was developed to approximate a constant loading rate test.

An elevated temperature data sheet (table LXIX) is based on these results, and an estimated (creep-extracted) shear stress versus shear strain curve has been plotted (figure 80). The specimen after failure is shown in figure 81.

TABLE LXIX. FILAMENTARY LAMINATE STATIC PROPERTY DATA

Material System: 104 Glass Fabric/Epoxy Lam Orient: [0/90] Woven
 Load Orient: 0°
 Type Loading: Tension ☐, Comp ☐, Shear ☒, Interlam Shear ☐
 Type Test Specimen: Pure Shear Picture Frame /H/C Sandwich
 Soak at Temp 350 °F for .33 Hr. Test Temp 350 °F

Property	Batch No.						
	Spec Ident	(1)					Ave.
Stress (Ksi)	P_1	1.10					1.10
	$F_{.85}$	2.80					2.80
	$F_{.70}$	4.05					4.05
	F at $2/3 \epsilon_1^{ult}$	5.25					5.25
	F^{ult}	6.85					6.85
Modulus $E, G \times 10^{-6}$	E or G (primary)	.50					.50
	E' or G' (secondary)	---					---
Strain in./in.	Proportional Limit	ϵ_1	.00220				.00220
		ϵ_2	---				---
		ϵ_{45}	---				---
	Ultimate	ϵ_1	.0271				.0271
		ϵ_2	---				---
		ϵ_{45}	---				---

No. of Plies 12/Face Actual Laminate Thickness _____
 Spec Laminate Thickness: Max _____, Min _____, Nominal .012
 Properties based on: Nominal Thickness X ; Actual Thickness

Filament Count _____ /in. Void Content _____ % Ply Thick. _____ in.
 Fil Vol Fract 0. Resin Wt Fract 0. Lam Density _____ lb/in.³

Laminate: Tape or Matrix Desig 2387 resin Manuf. Narmco
 Scrim Cloth _____ Additives Used No fill'r
 Cure Spec _____

Comments: (1) Strain-gaged

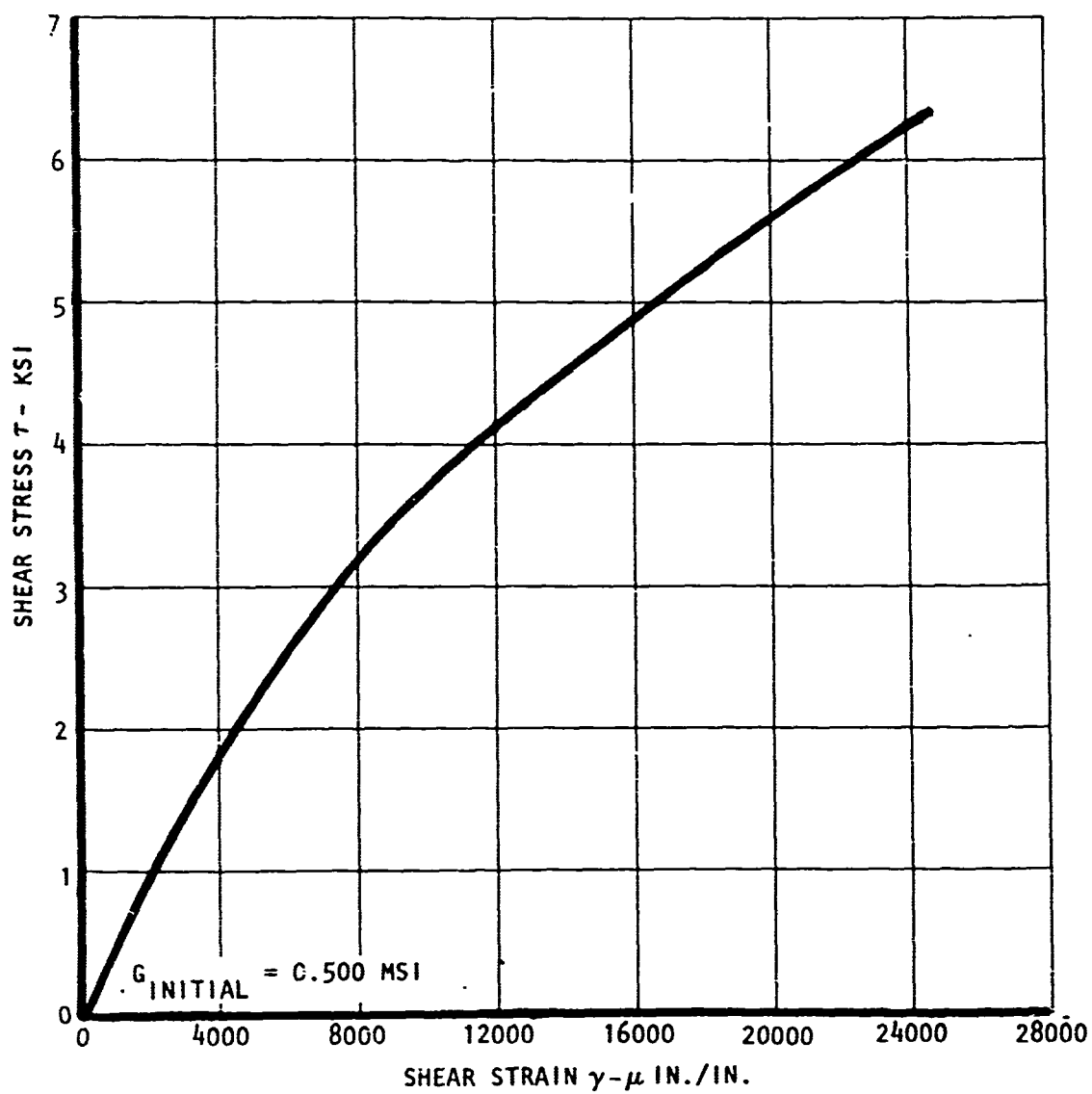


Figure 80. Shear Stress versus Shear Strain - 104 Glass Scrim Cloth - 350°F

Scrim Cloth Fatigue Strength

Fatigue test data for the longitudinal scrim cloth/2387 resin room temperature specimens are presented in the form of a conventional S-N curve (figure 82). The ordinate is in terms of percentage of the ultimate tensile strength, which was chosen as 36.6 ksi at the time the fatigue tests were conducted. This is so close to the final average tensile ultimate (35.95 ksi) that the curve was not replotted to the later value.

It is significant to note that while the curve follows a typical shape, the relative percentage is well above that of most of the typical structural metallic materials.

The test was conducted for a single R factor of 0.10 to avoid load reversal on the specimen. The data are unusually consistent for fatigue results, and a trend curve has been plotted through the lower values.

Scrim Cloth Creep Strength

Three creep tests of the 104 glass fabric/2387 resin laminate were originally scheduled. The creep test of the initial 12-ply (longitudinal) laminate at 350° F was terminated without a failure after increasing the stress to about 85 percent of the average static elevated temperature strength. Initial loading of the specimen was up to an 80-percent strength level. After 382 hours of this load without creep, the load was raised to 82.5 percent for 23 hours and then raised to 85 percent to the termination of the test.

No noticeable creep was observed at the 82.5 percent load, but after application of 85 percent, a relatively steady increase in strain gage reading was observed as noted in figure 83. After 580 hours, a very rapid increase in strain was observed, which soon resulted in loss of gage readings but no failure of the specimen. Loading was maintained for 4 days longer (677.2 hours from start); then the specimen was unloaded for inspection.

An electrical check of the gage confirmed an open grid circuit. This obviously was the cause of the rapid increase in readings over the 1-hour interval. There is no way of knowing whether or not some of the apparent creep prior to this time was also caused by gage failure.

There was a very severe darkening of the specimen, the surface being almost black. There may also have been some embrittlement of the material because when the specimen was accidentally dropped, both end tabs broke off.

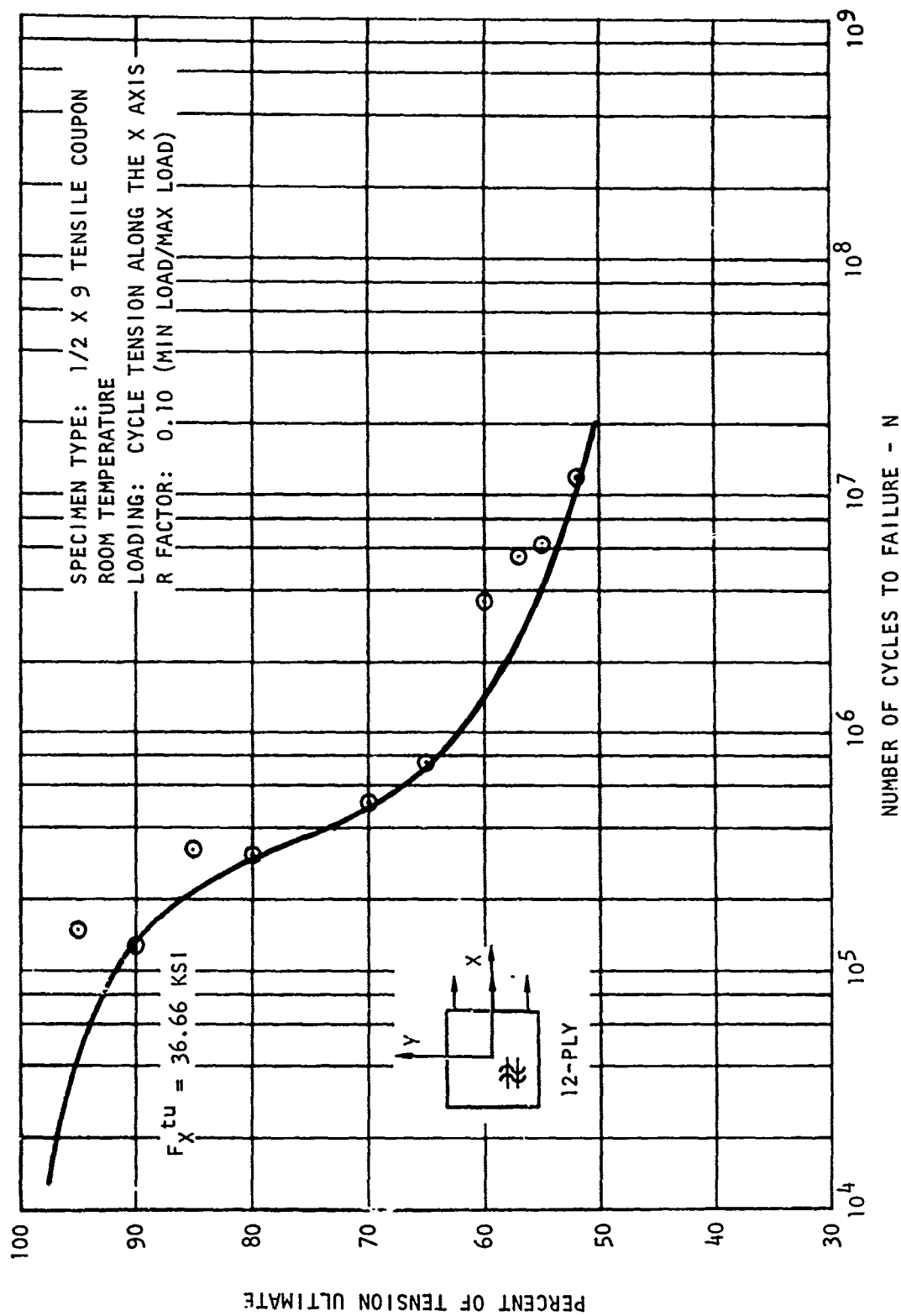


Figure 82. S-N Curve for 104 Fabric/Epoxy 12-Ply

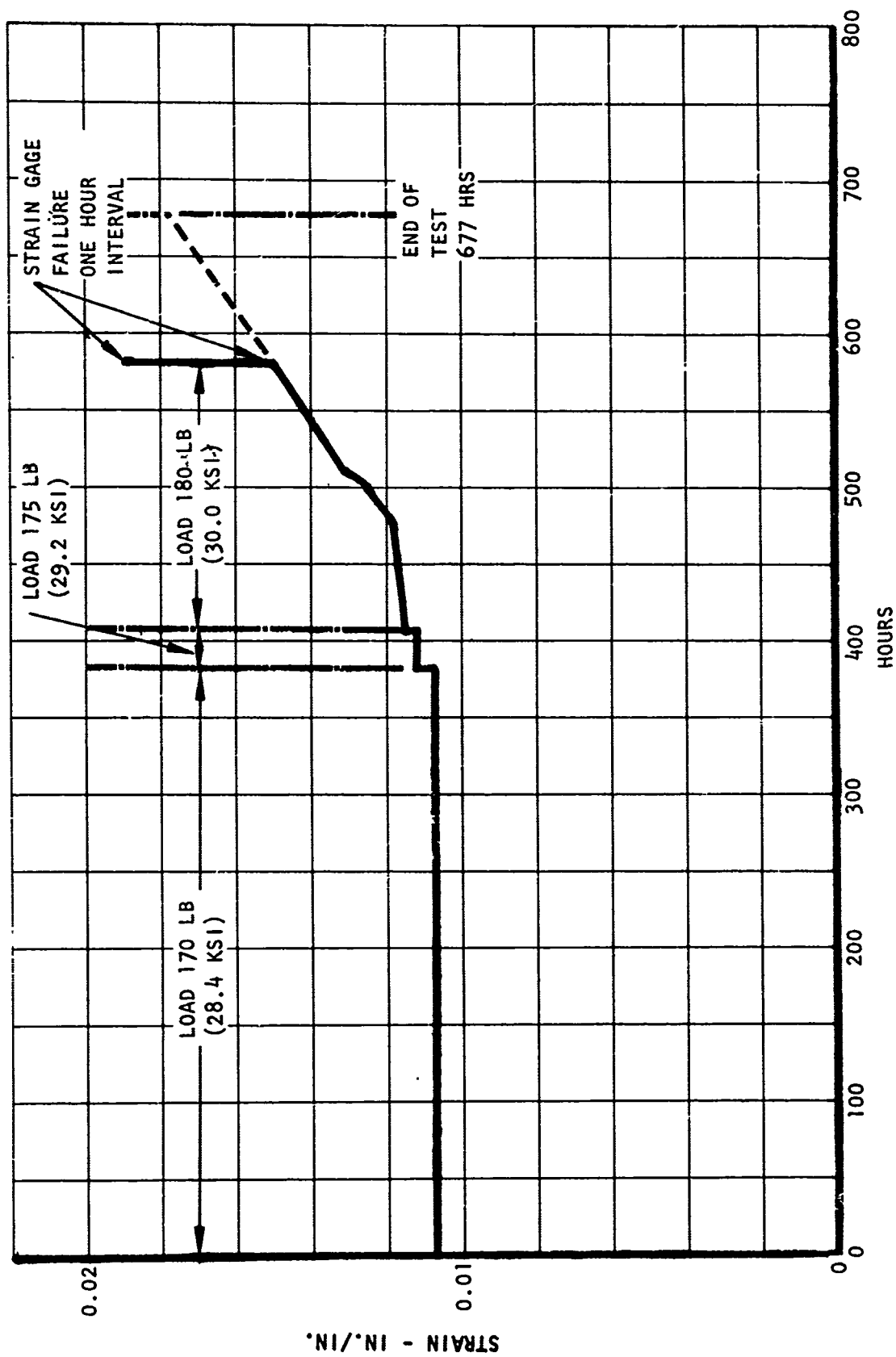


Figure 83. Strain versus Time for 104 Glass Creep Test

As a result of the high percentage load and relatively long life without significant creep, it was decided to test the remaining two creep specimens statically at 350° F. It is suspected that one reason for the scatter in elevated temperature tensile strength might be the sensitivity to postcure. (Previous test results varied from 26 to 43 ksi.) To evaluate this, the two remaining creep specimens were postcured for 14 hours at 350° F and then static tested at 350° F. Test results are given under the section on scrim cloth tensile strength.

Scrim Cloth Thermal Coefficient

Coefficient of thermal expansion data for the 104 glass fabric/5505 resin laminate were based on back-to-back strain gages on a 1- x 9-inch, 12-ply laminate. Differences in readings between the two sides indicated that considerable warpage occurred when the specimen was heated. Results are based on the averaged readings of the back-to-back gages of the unrestrained laminate. The method of calculating the results, using the strain gage thermal characteristics is shown in table LXX. The resulting coefficient of thermal expansion data for the laminate are given in figure 84.

NUCLEAR BLAST EFFECTS ON BORON/EPOXY LAMINATES

INTRODUCTION

Nuclear blast effects are normally considered to fall into three categories. Two of these, nuclear radiation and thermal shock, are of a specialized nature and merit separate consideration in the acquisition of basic material allowable data. The third environment, overpressure, is indistinguishable from any other type of dynamic airload, and can be handled in the same manner as other mechanical loadings.

To determine the nuclear radiation effect on boron/epoxy composites, mechanical property test coupons were exposed in a nuclear reactor to different periods of time. Thermal shock effects from nuclear blasts were simulated through the use of quartz heating lamps with the test coupons held under load prior to imposing the thermal shock. The degree of degradation was determined by comparison of the remaining strength with strength data from basic allowable tests on unexposed material.

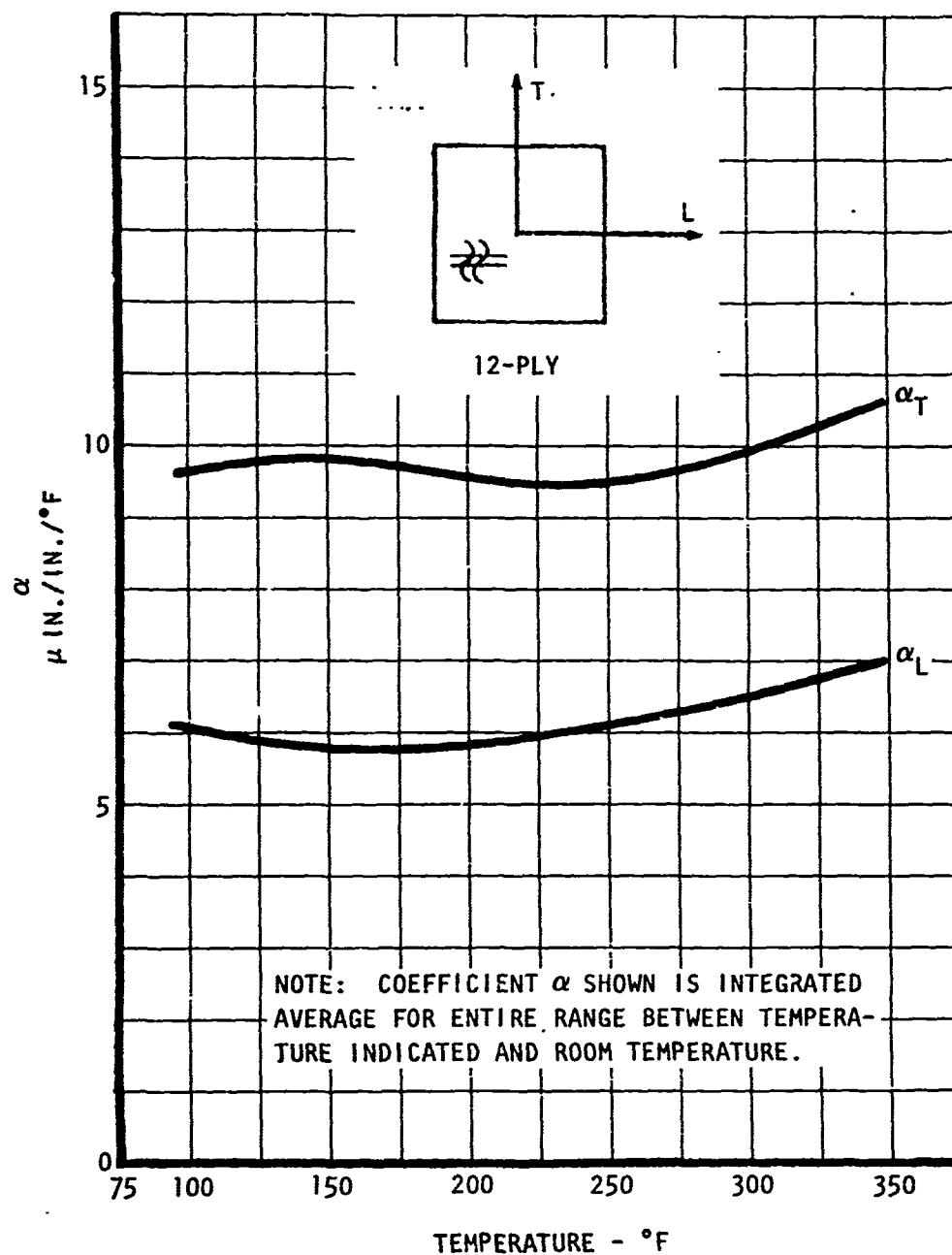


Figure 84. Integrated Average Coefficient of Thermal Expansion vs Temperature — 104 Glass Scrim Cloth

Test Specimens

The boron/epoxy test specimens of table LXXI were fabricated per the configuration of figures 85 through 87. A 104 glass balance ply was used on both the crossply and unidirectional orientation.

Eight of the thermal shock coupons (four tension, four compression) were submitted to the Air Force Materials Laboratory at Wright Patterson Air Force Base, Ohio, for the following high-temperature protective coating. The selected samples were primed with a catalyzed silicone primer to a dry film thickness of 1.0 ± 0.2 mil, and then top-coated with catalyzed white silicone topcoat in-house formulation No. AF-66 to a dry film thickness of 3.0 ± 0.2 mils. Formulation No. AF-66 is a white, highly reflective, emissive, high-gloss, high-temperature silicone primer and topcoat combination which was developed to meet the requirements for use on high-speed (mach 3) aircraft (reference 2).

NUCLEAR RADIATION

Test Loads and Test Procedure

The primary radiation effect of interest to the degradation of materials is considered to be from fast neutron radiation. On the basis of aircraft vulnerability requirements, an exposure of 1×10^{12} neutrons per square centimeter was selected as an integrated single exposure, with six such exposures used to simulate a typical expected lifetime air vehicle exposure.

Irradiation of the boron/epoxy specimens was conducted at the 2-mega-watt Battelle Research Reactor (BRR Irradiation No. 1859). This facility is located 15 miles west of Columbus, Ohio, where the core of MTR-type aluminum fuel assemblies is suspended in demineralized water, 25 feet below a mobile bridge. Available unperturbed radiation levels at the core face are approximately:

Fast-neutron flux

$$1 \times 10^{13} \text{ n}/(\text{cm}^2)(\text{sec})$$

Thermal-neutron flux

$$2 \times 10^{13} \text{ n}/(\text{cm}^2)(\text{sec})$$

Gamma dose rate

$$1 \times 10^8 \text{ r per hour}$$

TABLE LXXI. TEST SPECIMENS - NUCLEAR BLAST EFFECTS

Configuration	Environment	Quantity	Orientation
Tension Standard 1/2 x 9 IITRI coupon	Control	4	$[0]_{6T}$
		4	$[0/\pm 45/0]_{2S}$
	Thermal shock	8	$[0]_{6T}$
		8	$[0/\pm 45/0]_{2S}$
	Neutron radiation	6	$[0]_{6T}$
		6	$[0/\pm 45/0]_{2S}$
Compression 1 x 5 single-face compression sandwich specimen	Thermal shock	8	$[0]_{6T}$
		8	$[0/\pm 45/0]_{2S}$
	Neutron radiation	6	$[0]_{6T}$
		6	$[0/\pm 45/0]_{2S}$
Interlaminar shear Standard short beam (0.25 x 0.60)	Neutron radiation	6	$[0]_{6T}$

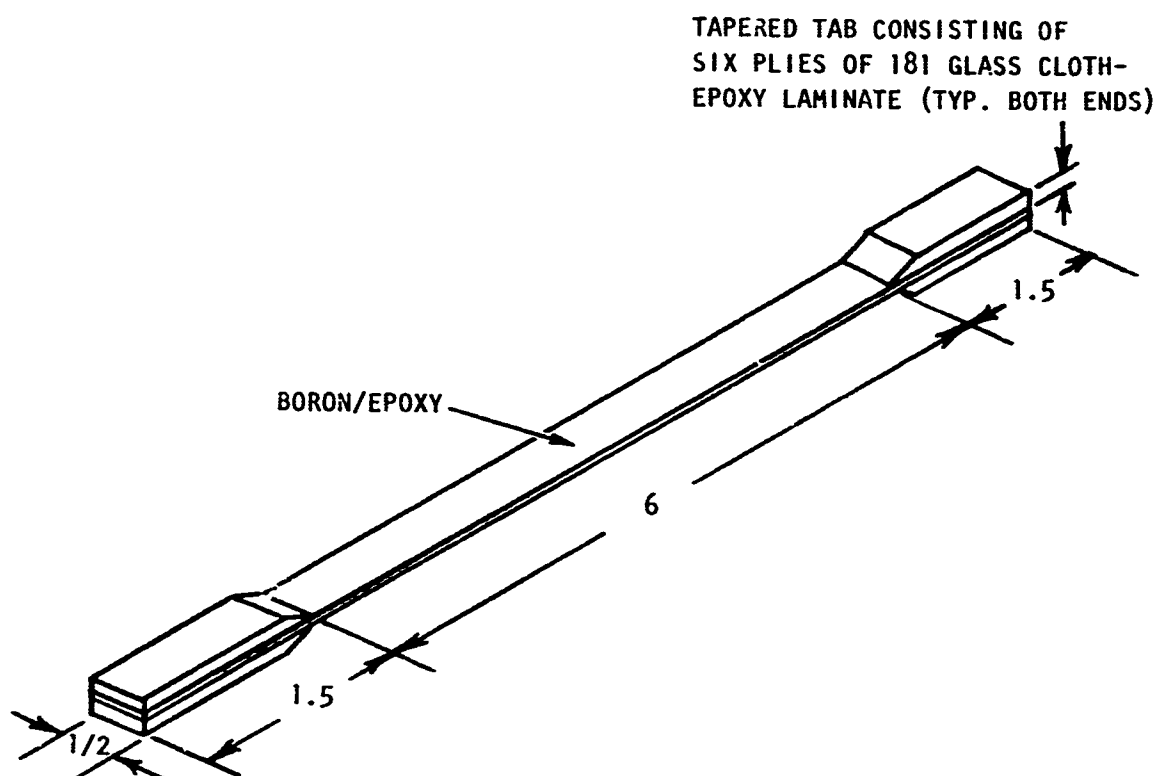


Figure 85. . Tension Specimen

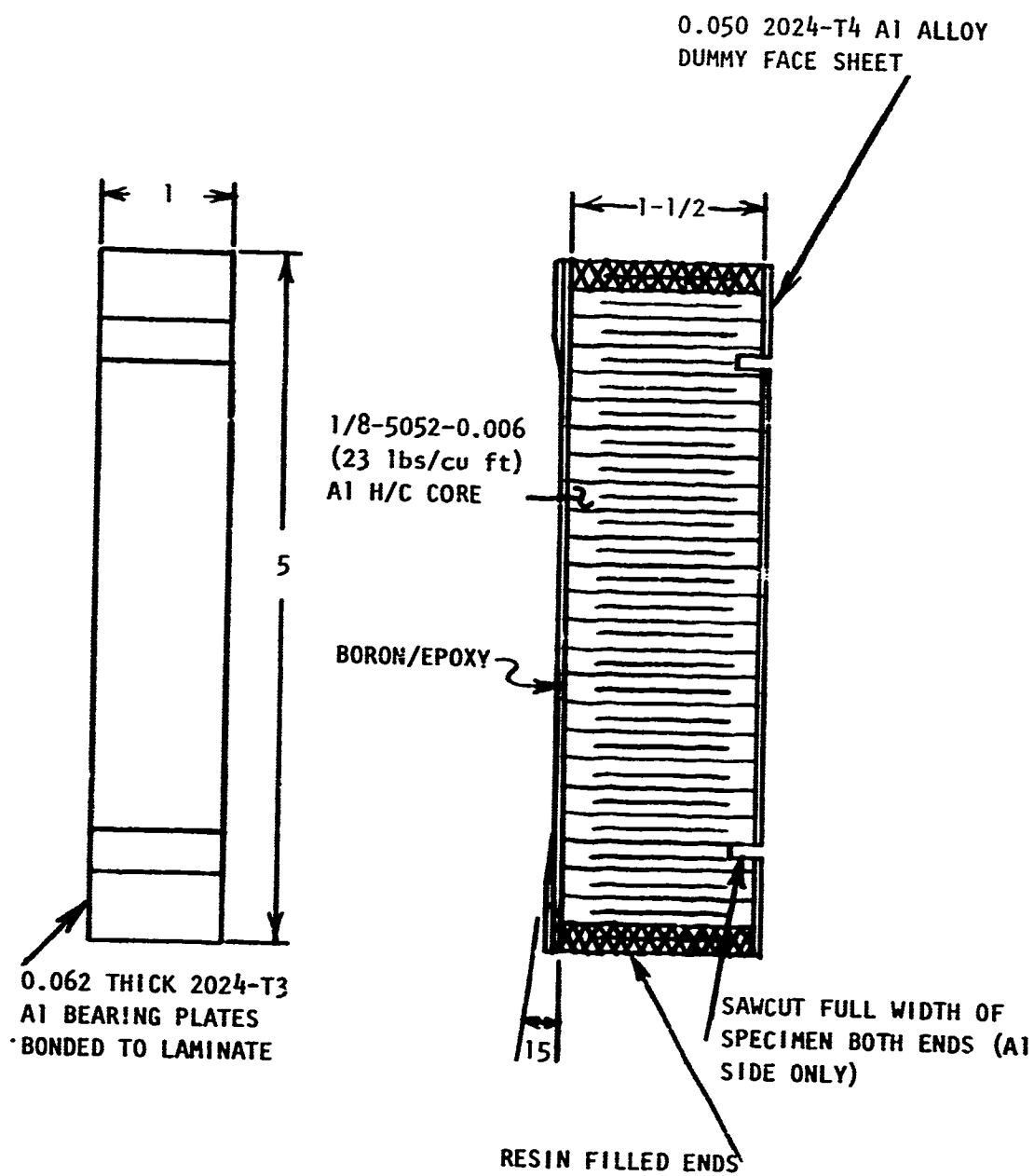
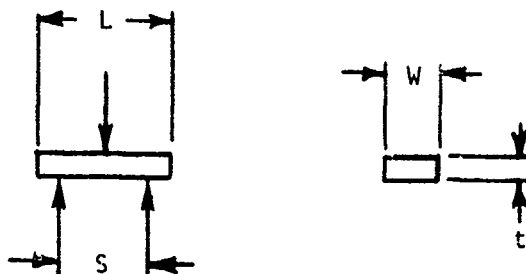


Figure 86. Compression Specimen



SPECIMEN DIMENSIONS

LENGTH (L) = 0.60 ± 0.01
 WIDTH (W) = 0.250 ± 0.003
 THICKNESS (t) = 0.060 TO 0.090

LOAD METHODS

$S = 0.4$
 OVERHANG MUST BE SAME
 OVER EACH END

LOAD AND REACTION SUPPORTS
 ARE 1/8 IN. RADIUS STEEL RODS.
 ALL FILAMENTS ARE 0° TO THE
 L DIMENSION.

Figure 87. Interlaminar Shear Test Specimen

The specimens were grouped into sample sets numbered 1 through 6. Each sample set was composed of one each of the following specimens: $[0]_C$ compression, $[0_2/\pm 45]_C$ compression, $[0]_C$ tension, and $[0_2/\pm 45]_C$ tension. The three small coupons of composite for interlaminar shear tests were placed one each in sample sets 1, 3, and 6. The samples were affixed to aluminum plates with aluminum foil molded to conform to the shapes of the specimens. A dosimeter wire was then attached to each assembly and the assemblies covered with a 20-mil cadmium wrapper to shield the samples from thermal neutrons. These assemblies were then double-sealed in polyethylene bags under a nitrogen atmosphere and irradiated, one side only, in a neutron flux of approximately 7×10^9 neutrons/cm²/sec for the prescribed times. Dose measurements indicated that the range of doses to the samples did not span the required 6×10^{12} neutrons/cm²; therefore, sample sets 3 and 5 were reirradiated. The integrated fast-neutron (>0.1 mev) doses were:

<u>Sample Set No.</u>	<u>Fast-Neutron Dose</u> (Tn/cm ²)
1	0.4
2	1.1
4	2.0
6	3.1
3	6.2
5	7.2

Reactor pool water leaked into the inner polyethylene bag during underwater handling. However, the samples were subsequently decontaminated using only clear water. A survey for removable surface contamination showed that all contamination had been removed by this method.

Test Results

Results of tension tests conducted on control coupons taken from the laminates to be incorporated into the nuclear radiation specimens are documented in table LXXII. Results of the irradiated specimens are documented in table LXXIII with photographs of the failed specimens presented as figures 88 through 92. All tests were performed at room temperature on an Instron Test Machine.

TABLE LXXII. TENSION TEST RESULTS FOR CONTROL SPECIMENS - RADIATION

Specimen No.	Orientation	Width (Inches)	Actual Thickness (Inches)	Nominal * Thickness (Inches)	Load (Pounds)	F _{tu} (Actual) (psi)	F _{tu} (Nominal) (psi)
3894-39-1	[0] _{6T}	0.498	0.0326	0.0312	2,740	168,700	176,300
3894-39-2	[0] _{6T}	0.511	0.0328	0.0312	2,970	177,100	186,200
					Average	172,900	181,300
3894-39-3	[0/±45/0] _{2S}	0.509	0.0427	0.0416	2,180	100,300	102,900
3894-39-4	[0/±45/0] _{2S}	0.510	0.0425	0.0416	2,220	102,400	104,600
					Average	101,300	103,700

* Based on nominal lamina thickness of 0.0052 inch

TABLE LXXIII. TEST RESULTS OF IRRADIATED SPECIMENS

Test	Specimen No.	Radiation Sample Set No.	Orientation	Width (Inches)	Actual Thickness (Inches)	Nominal Thickness (Inches)	Load (Pounds)	F_{tu} (Actual) (psi)	F_{tu} (Nominal) (psi)
Tension	3894-39-R1-1	1	[0] _{6T}	0.498	0.033	0.0312	2,730	166,100	175,700
	3894-39-R1-2	2	↕	0.491	↕	↕	2,530	162,300	171,600
	3894-39-R1-3	3	↕	0.498	↕	↕	2,730	166,100	175,600 Avg
	3894-39-R1-4	4	↕	0.494	↕	↕	2,720	166,800	176,500
	3894-39-R1-5	5	↕	0.502	↕	↕	2,960	178,600	189,000
	3894-39-R1-6	6	[0] _{6T}	0.497	0.033	0.0312	2,800	170,700	180,600
	3894-39-R3-1	1	[0/±45/0] _{2S}	0.491	0.042	0.0416	2,100	101,800	102,800
	3894-39-R3-2	2	↕	0.479	0.043	↕	1,950	94,600	97,800
	3894-39-R3-3	3	↕	0.498	0.042	↕	2,175	103,900	104,900 Avg
	3894-39-R3-4	4	↕	0.502	0.043	↕	2,000	92,600	95,700
	3894-39-R3-5	5	↕	0.494	0.043	↕	2,250	105,900	109,400
	3894-39-R3-6	6	[0/±45/0] _{2S}	0.501	0.043	0.0416	2,175	100,900	104,300
Compression	3894-39-1A-1	1	[0] _{6T}	0.961	0.033	0.0312	7,180	226,400	239,400
	3894-39-1A-2	2	↕	0.952	↕	↕	5,600	178,200	188,500
	3894-39-1A-3	3	↕	0.978	↕	↕	5,475	169,600	179,400 Avg
	3894-39-1B-4	4	↕	0.928	↕	↕	4,900	160,000	169,200
	3894-39-1B-5	5	↕	0.964	↕	↕	4,880	153,400	162,200
	3894-39-1B-6	6	[0] _{6T}	0.964	0.033	0.0312	4,900	154,000	162,900
	3894-39-3A-1	1	[0/±45/0] _{2S}	0.975	0.043	0.0416	6,900	164,900	170,400
	3894-39-3A-2	2	↕	0.959	↕	↕	6,050	146,700	151,600
	3894-39-3A-3	3	↕	0.924	↕	↕	6,575	165,400	171,000 Avg
	3894-39-3B-4	4	↕	0.939	↕	↕	6,900	170,800	176,600
	3894-39-3B-5	5	↕	0.944	↕	↕	6,650	163,800	169,300
	3894-39-3B-6	6	[0/±45/0] _{2S}	0.971	0.043	0.0416	7,720	184,800	191,100
Interlaminar Shear	3894-39-1A	1	[0] _{6T}	0.258	0.033	0.0312	113	9,900	10,500
	3894-39-1B	1	↕	0.258	↕	↕	120	10,500	11,100
	3894-39-3A	3	↕	0.265	↕	↕	111	9,500	10,000 Avg
	3894-39-3B	3	↕	0.255	↕	↕	128	11,400	12,000
	3894-39-6A	6	↕	0.259	0.033	↕	119	10,400	11,000
	3894-39-6B	6	[0] _{6T}	0.264	0.032	0.0312	126	10,800	11,400

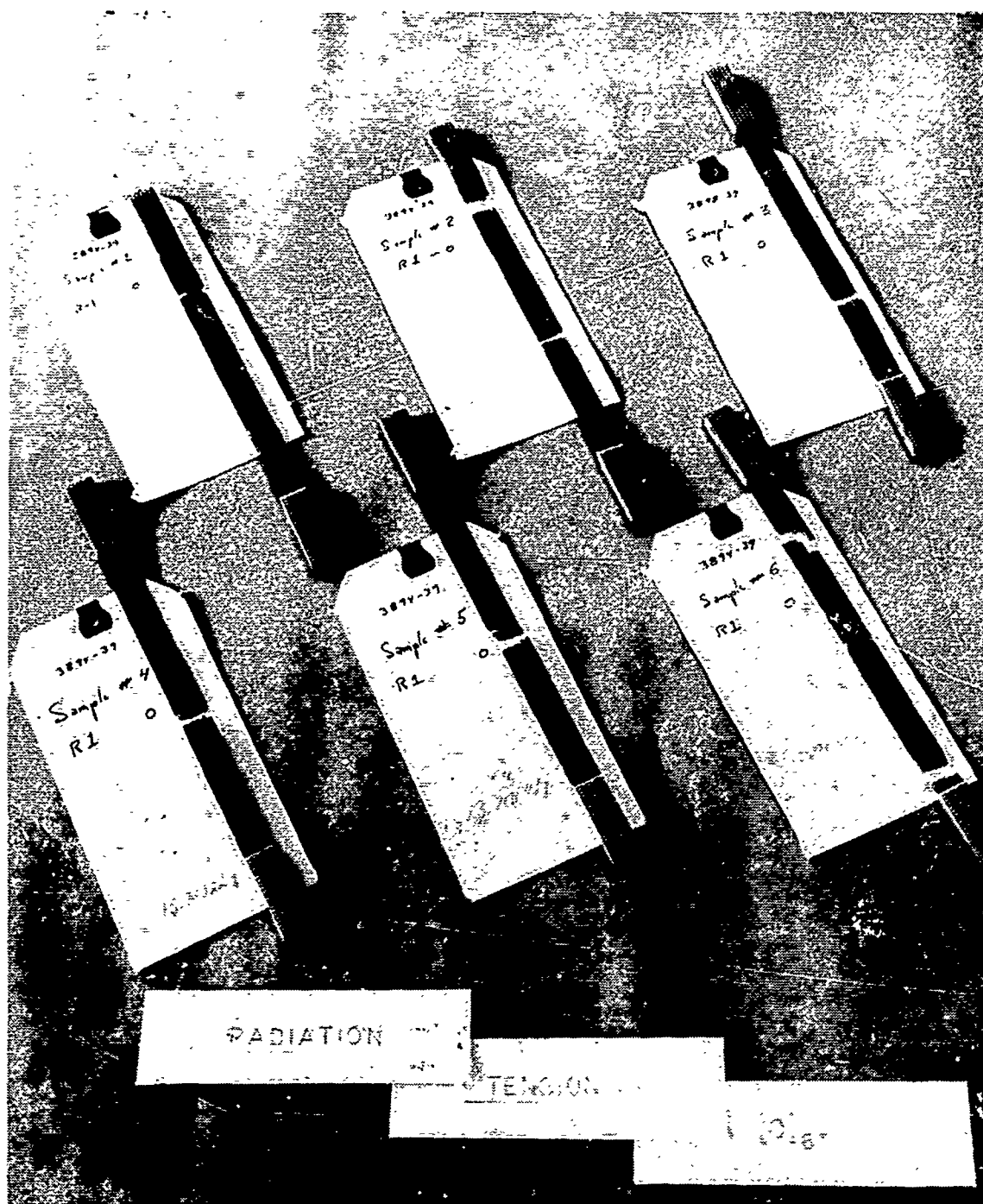


Figure 88. Failed Radiation $[0]_{6T}$ Tension Specimens

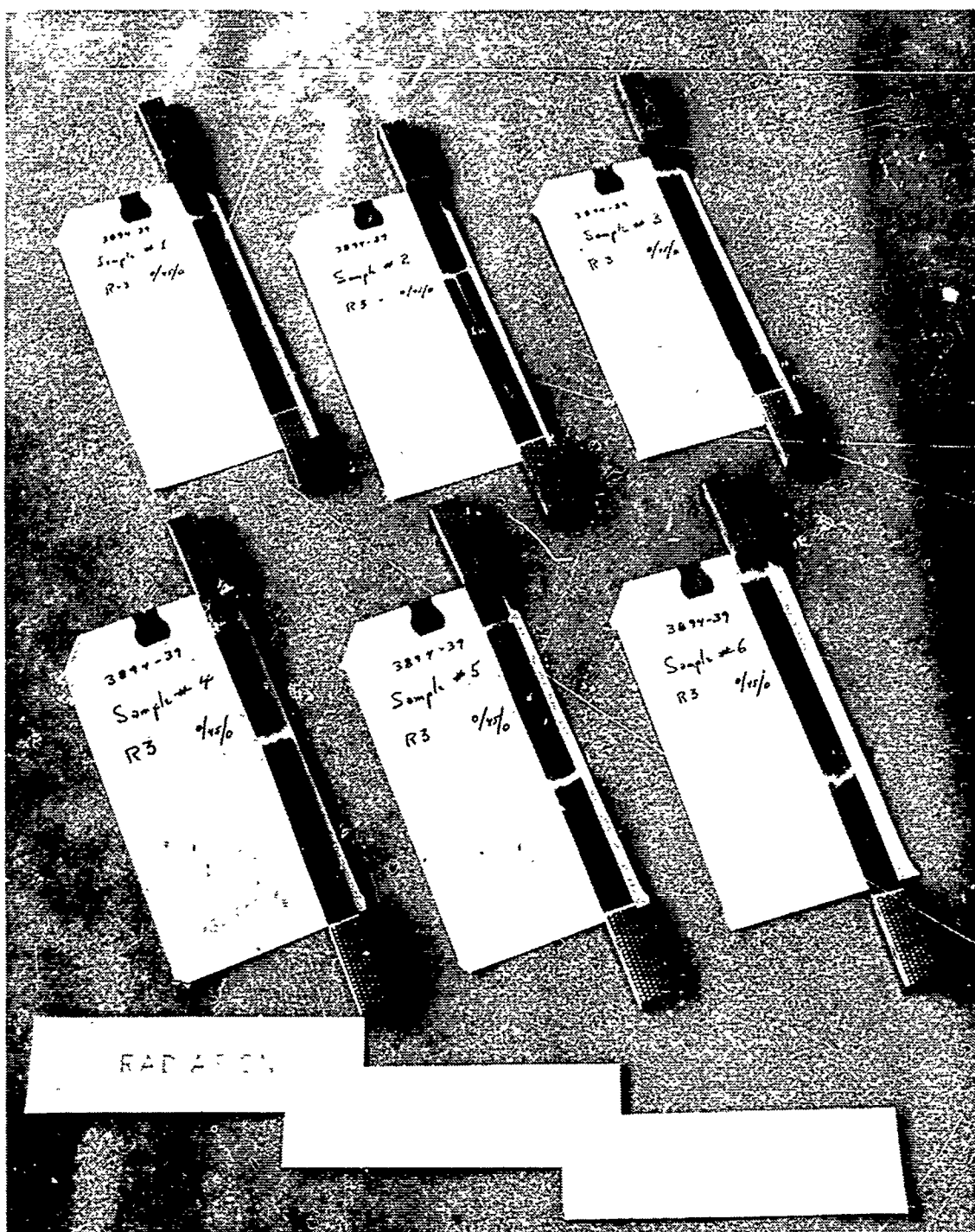


Figure 89. Failed Radiation $[0/\pm 45/0]_{2S}$ Tension Specimens

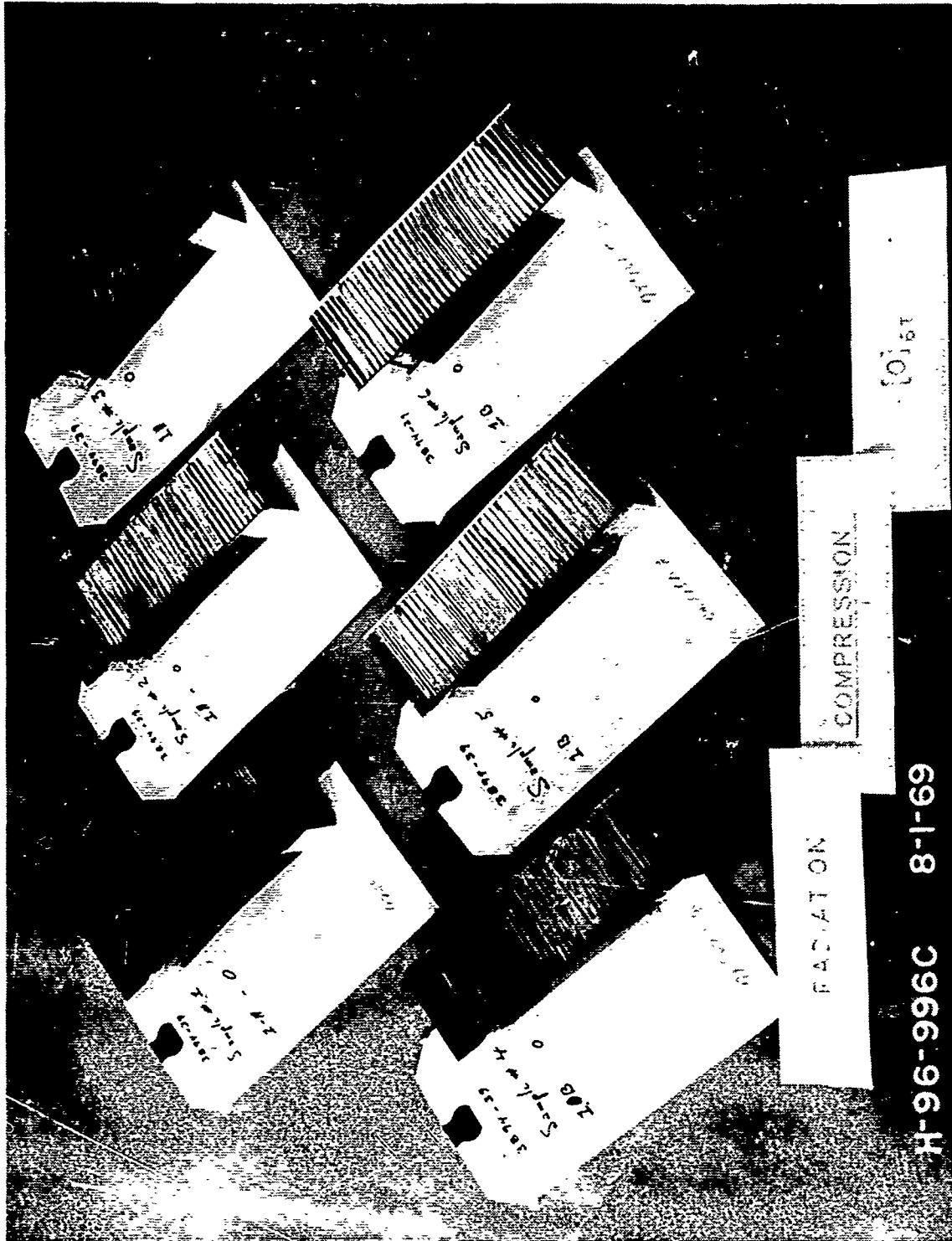


Figure 90. Failed Radiation [0]_{6T} Compression Specimens

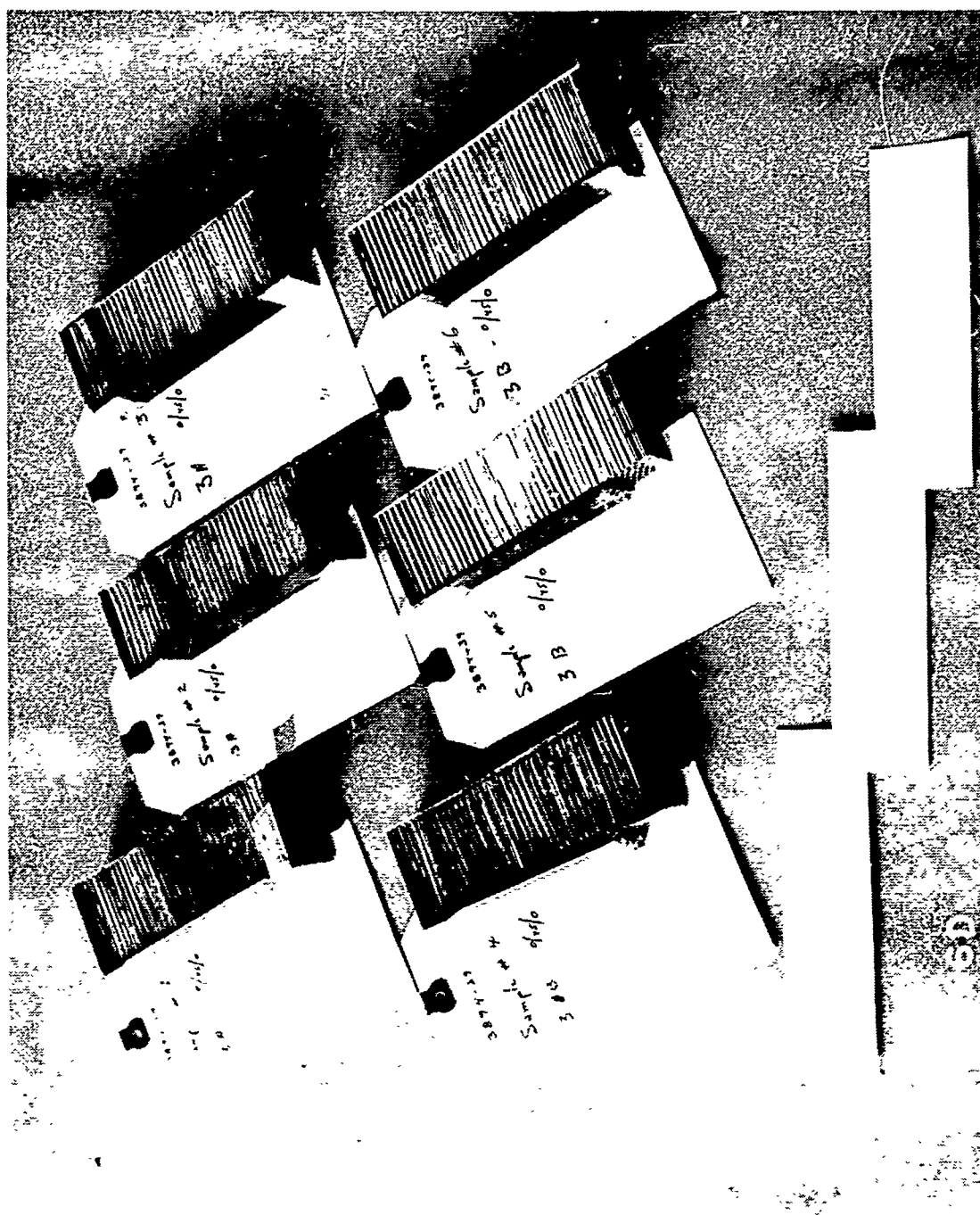


Figure 91. Failed Radiation [0/45/0]_{2S} Compression Specimens

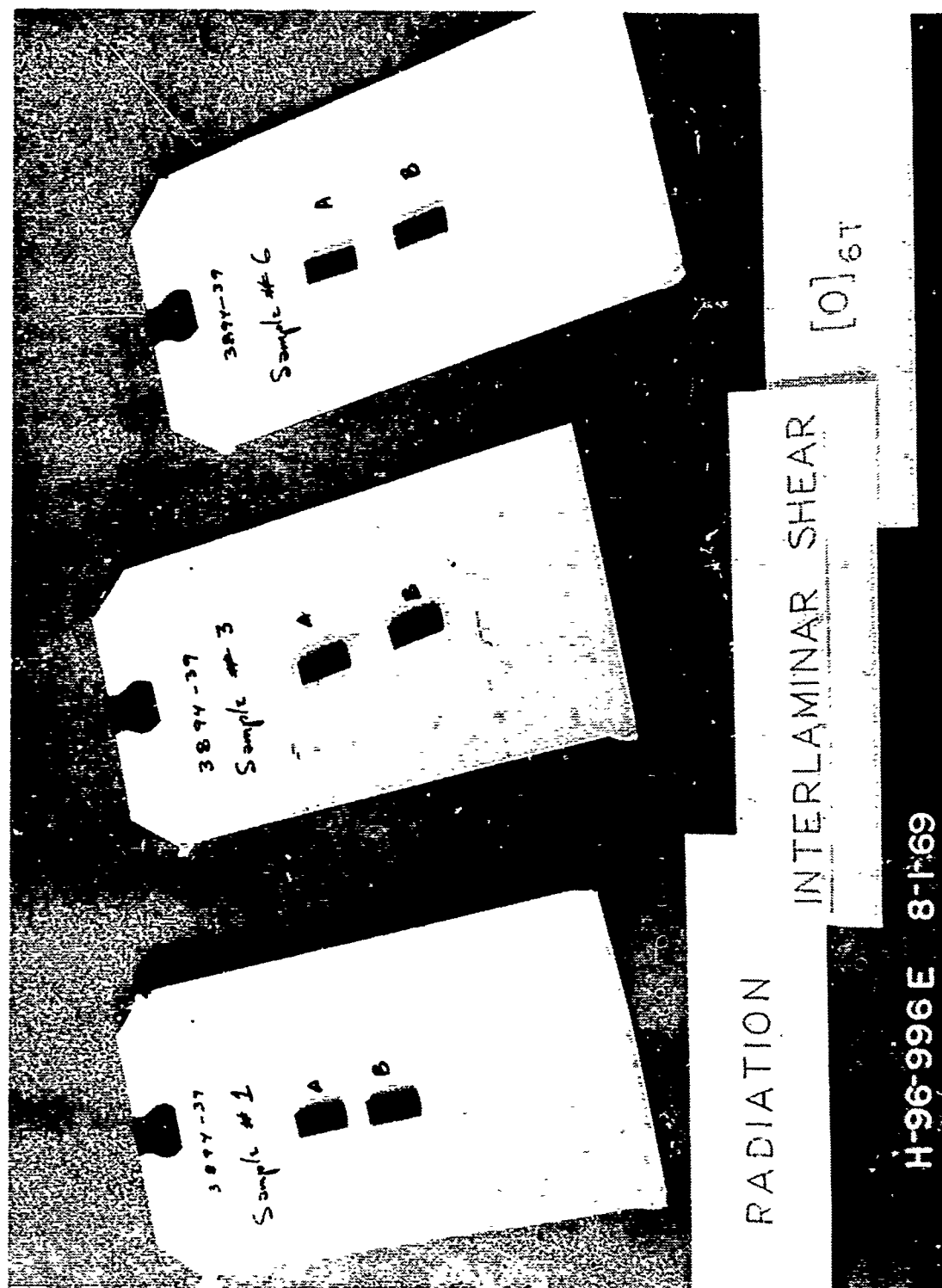


Figure 92. Failed Radiation [O]₆T Interlaminar Shear Specimens

THERMAL SHOCK

Test Loads and Test Procedure

The analytical determination of an integrated thermal input rate, based on 50 calories per square centimeter per aircraft vulnerability requirements, is shown as figure 93. Calculations were made for a 0.050 external aircraft aluminum skin painted white. A calibration was made to position quartz lamps to duplicate this response as closely as possible using 0.050 aluminum painted black. Three quartz lamps of 2,000 watts each at 230 to 250 volts ac, positioned 3/4 inch from the front face of the specimen, produced 350° F on the back face in 8 seconds. All boron/epoxy specimens were tested with the lamps held at this position, with all specimens painted black on the exposure side except those having the AF-66 thermal protective coating. All thermal shock tests were conducted using an MB tensile machine with a 20,000-pound constant load maintainer, calibrated 16 June 1969. The test specimens were preloaded to different stress levels and held under load while imposing the thermal shock; the loading was continued to failure after the heat was dissipated with an air blast at 90 psi. Photographs of the test setup are shown in figures 94, 95, and 96.

Test Results

Results of tension tests conducted on control coupons taken from the laminates to be incorporated into the thermal shock specimens are documented in table LXXIV. Results of the thermal shock tests are documented in table LXXV; photographs of the failed specimens are presented in figures 97 through 100.

CONCLUSIONS

On the basis of ultimate tensile and/or interlaminar shear strength, there is no degradation of boron/epoxy $[0]_C$ and $[0_2/\pm 45]_C$ laminates when subjected to fast-neutron (>0.1 mev) doses ranging from 0.4 to 7.2 Tn/cm². However, considerable degradation of ultimate tensile strength was experienced by similar composites when subjected to thermal shock loading, as shown in figure 101, unless an adequate thermal protective coating is utilized. No attempt is made to correlate the compression test data since the single-face test specimens were more sensitive to face-to-core bonding and stabilization than to the nuclear radiation or thermal shock environments.

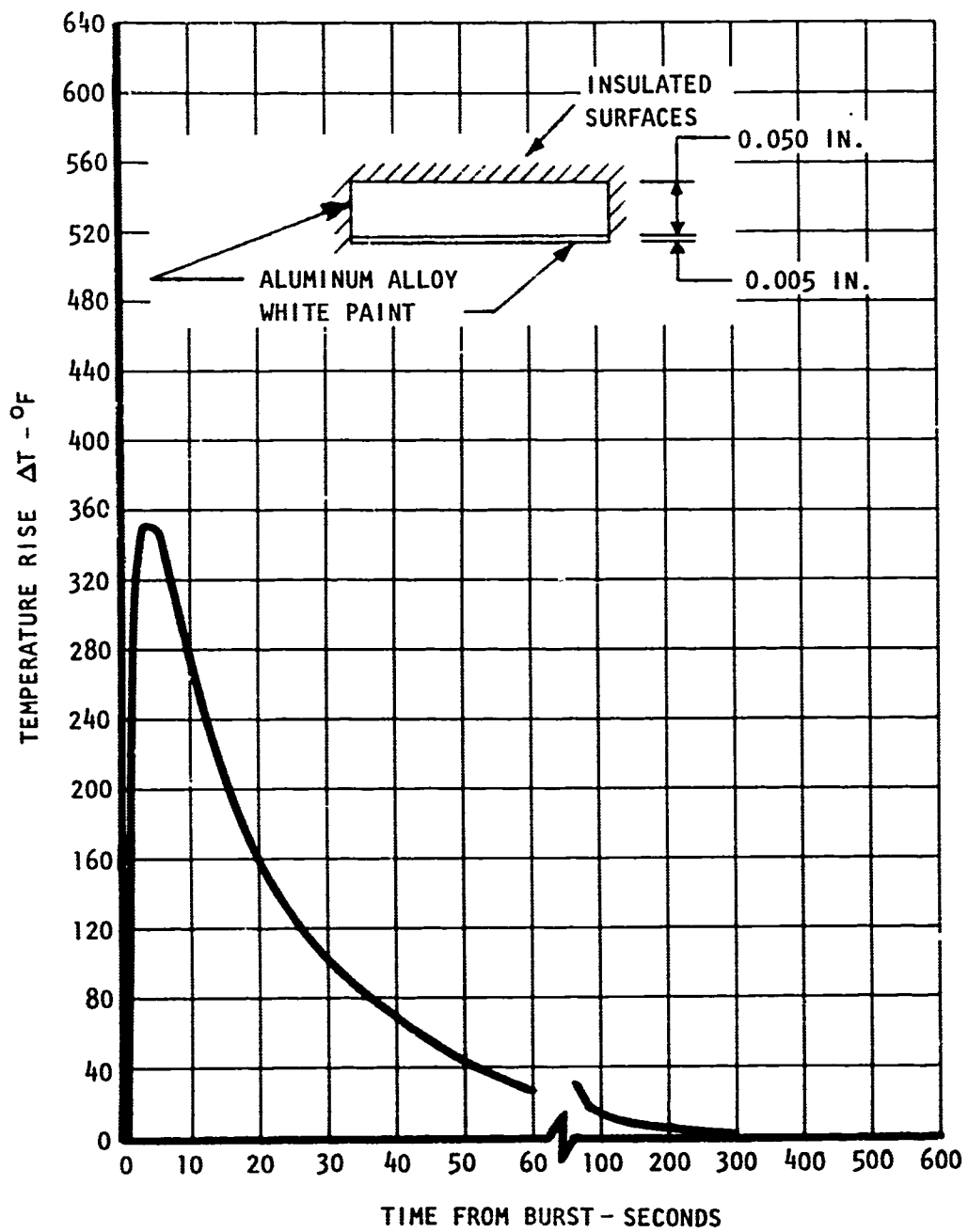


Figure 93. Thermal Input

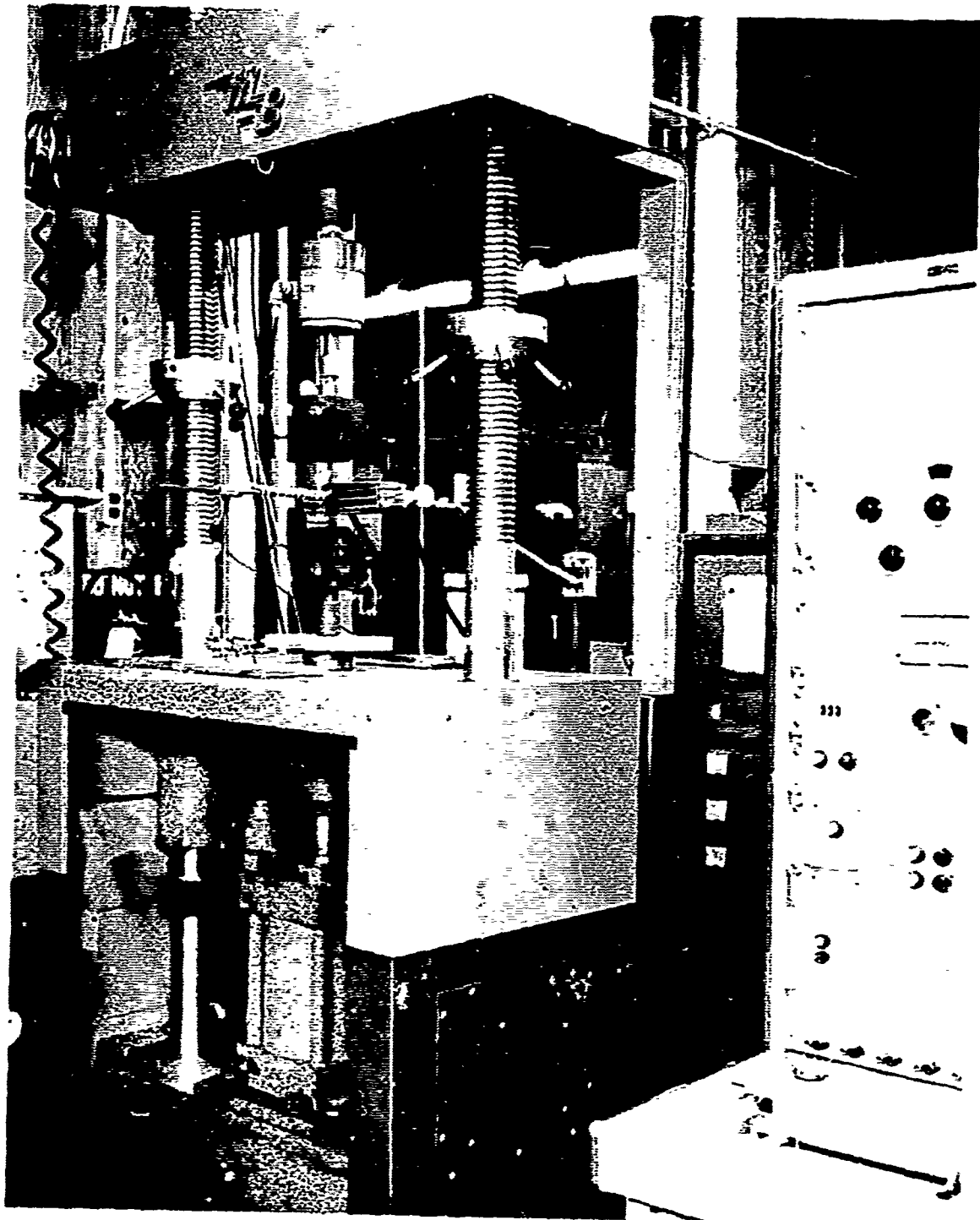


Figure 94. Thermal Shock Test Setup

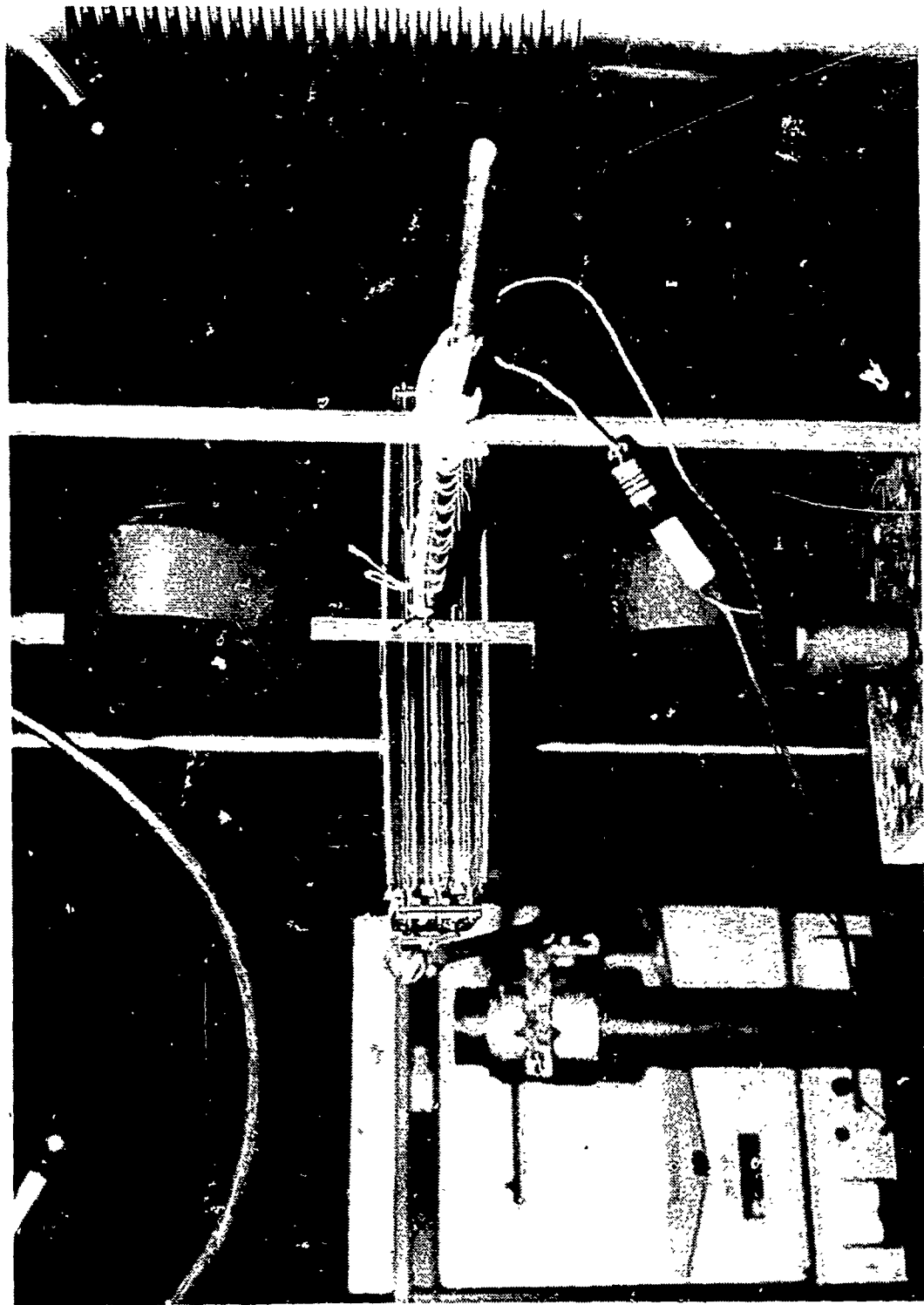


Figure 95. Combined Thermal Shock and Tension Test Setup

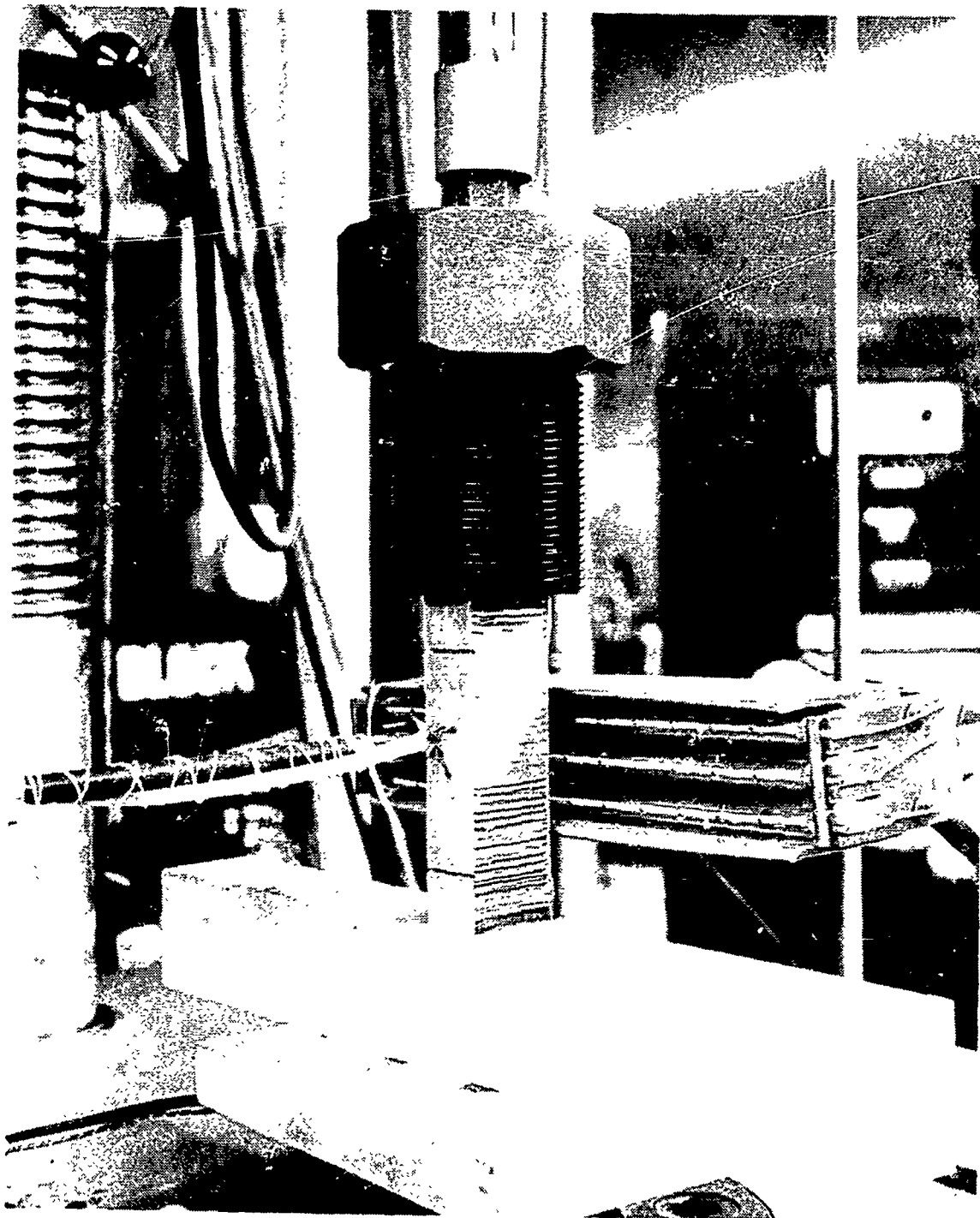


Figure 96. Combined Thermal Shock and Compression Test Setup

TABLE LXXIV. TENSION TEST RESULTS OF CONTROL SPECIMENS - THERMAL SHOCK

Specimen No.	Orientation	Width (Inches)	Actual Thickness (Inches)	Nominal Thickness (Inches)	Load (Pounds)	f_{tu} (Actual) (psi)	f_{tu} (Nominal) (psi)
3894-38-1	[0] _{6T}	0.508	0.0330	0.0312	2,870	171,200	181,000
3894-38-2	[0] _{6T}	0.511	0.0325	0.0312	2,870	<u>172,812</u>	<u>180,012</u>
					Average	172,006	180,544
3894-38-3	[0/±45/0] _{2S}	0.498	0.0430	0.0416	2,230	104,137	107,641
3894-38-4	[0/±45/0] _{2S}	0.510	0.0425	0.0416	1,880	<u>86,734</u>	<u>88,610</u>
					Average	95,435	98,125

TABLE LXXV. TEST RESULTS OF THERMAL SHOCK SPECIMENS

Test	Specimen No.	Back Face Preload at Temp (°F)	Heat Input (Pounds)	Orientation	Width (Inches)	Actual Thickness (Inches)	Nominal Thickness (Inches)	Load (Pounds)	F _{tu} (Actual) (psi)	F _{tu} (Nominal) (psi)
Combined thermal shock and longitudinal tension	3894-38-1-1	-	726	[0] _{6T}	0.489	0.033	0.0312	2,600	161,100	170,400
	3894-38-1-2	-	714	↓	0.498	0.034	↓	2,428	143,300	156,200
	3894-38-1-3	-	1,786	↓	0.500	0.033	↓	1,786	108,200	114,400
	3894-38-1-4	-	1,340	↓	0.487	0.033	↓	2,485	154,600	163,500
	3894-38-1-5	-	1,490	↓	0.493	0.034	↓	2,580	153,900	167,700
	3894-38-1-6	-	1,700	↓	0.499	0.034	↓	2,440	143,800	156,700
	3894-38-1-7*	250	1,800	↓	0.485	0.033	↓	2,600	162,400	171,800
	3894-38-1-8*	250	1,800	[0] _{6T}	0.489	0.033	0.0312	2,300	142,500	150,700
	3894-38-3-1	450	457	[0/±45/0] _{2S}	0.500	0.043	0.0416	1,730	80,400	83,100
	3894-38-3-2	-	456	↓	0.497	0.043	↓	1,800	84,200	87,000
	3894-38-3-3	460	1,228	↓	0.497	0.043	↓	1,228	57,400	59,300
	3894-38-3-4	420	886	↓	0.498	0.043	↓	1,929	90,000	93,100
	3894-38-3-5	460	1,140	↓	0.495	0.043	↓	1,773	83,200	86,100
	3894-38-3-6	460	1,143	↓	0.500	0.043	↓	1,700	79,000	81,700
	3894-38-3-7*	275	1,257	↓	0.499	0.043	↓	1,986	92,500	95,600
	3894-38-3-8*	270	1,243	[0/±45/0] _{2S}	0.489	0.043	0.0416	1,972	93,700	96,900
Combined thermal shock and compression	3894-38-1-1	100	2,014	[0] _{6T}	1.008	0.033	0.0312	2,014	60,500	64,000
	3894-38-1-2	100	1,000	↓	1.033	↓	↓	1,660	48,600	51,300
	3894-38-1-3	120	800	↓	1.018	↓	↓	2,800	83,300	88,100
	3894-38-1-4	130	800	↓	0.979	↓	↓	2,887	89,300	94,500
	3894-38-1-5	110	1,200	↓	1.029	↓	↓	1,600	47,100	49,800
	3894-38-1-6	-	400	↓	0.989	↓	↓	3,700	113,300	119,900
	3894-38-1-7*	-	2,000	↓	0.999	↓	↓	3,300	100,100	105,800
	3894-38-1-8*	110	2,000	[0] _{6T}	0.993	0.033	0.0312	4,180	127,500	134,900
	3894-38-3-1	-	-	[0/±45/0] _{2S}	1.018	0.043	0.0416	-	-	-
	3894-38-3-2	130	1,800	↓	1.015	↓	↓	3,600	82,400	85,200
	3894-38-3-3	140	1,000	↓	0.996	↓	↓	3,320	77,500	80,100
	3894-38-3-4	130	2,430	↓	1.000	↓	↓	2,430	56,500	58,400
	3894-38-3-5	130	2,000	↓	1.016	↓	↓	2,000	45,700	47,300
	3894-38-3-6	-	0	↓	1.027	↓	↓	3,943	89,200	92,200
	3894-38-3-7*	110	2,000	↓	1.002	↓	↓	4,945	118,600	118,600
	3894-38-3-8*	110	1,986	[0/±45/0] _{2S}	1.008	0.043	0.0416	3,714	85,600	88,500

NOTE: * Denotes specimens having thermal protective coating

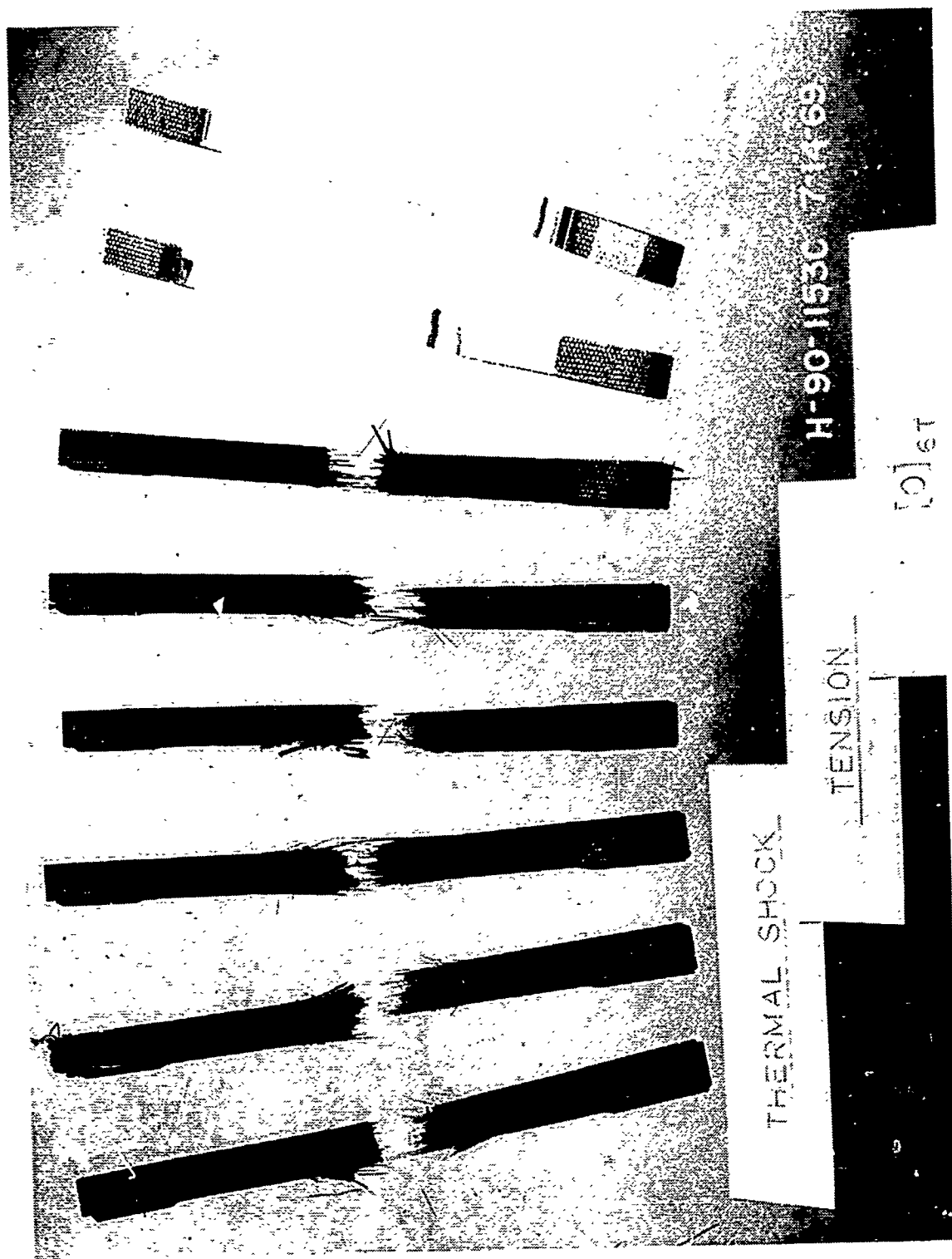


Figure 97. Failed Thermal Shock [0]_{6T} Tension Specimens

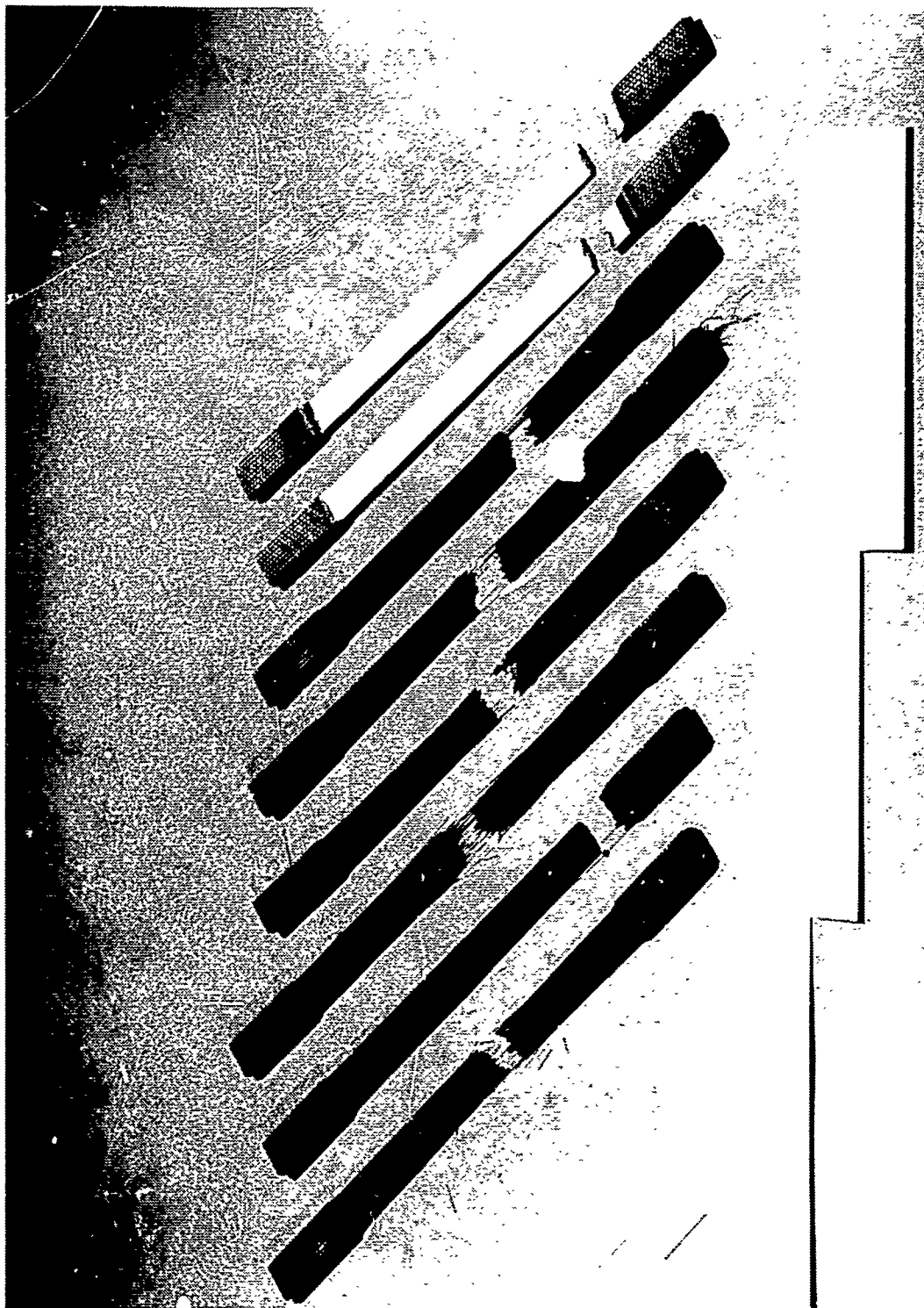


Figure 98. Failed Thermal Shock [0/+45/0]_{2S} Tension Specimens

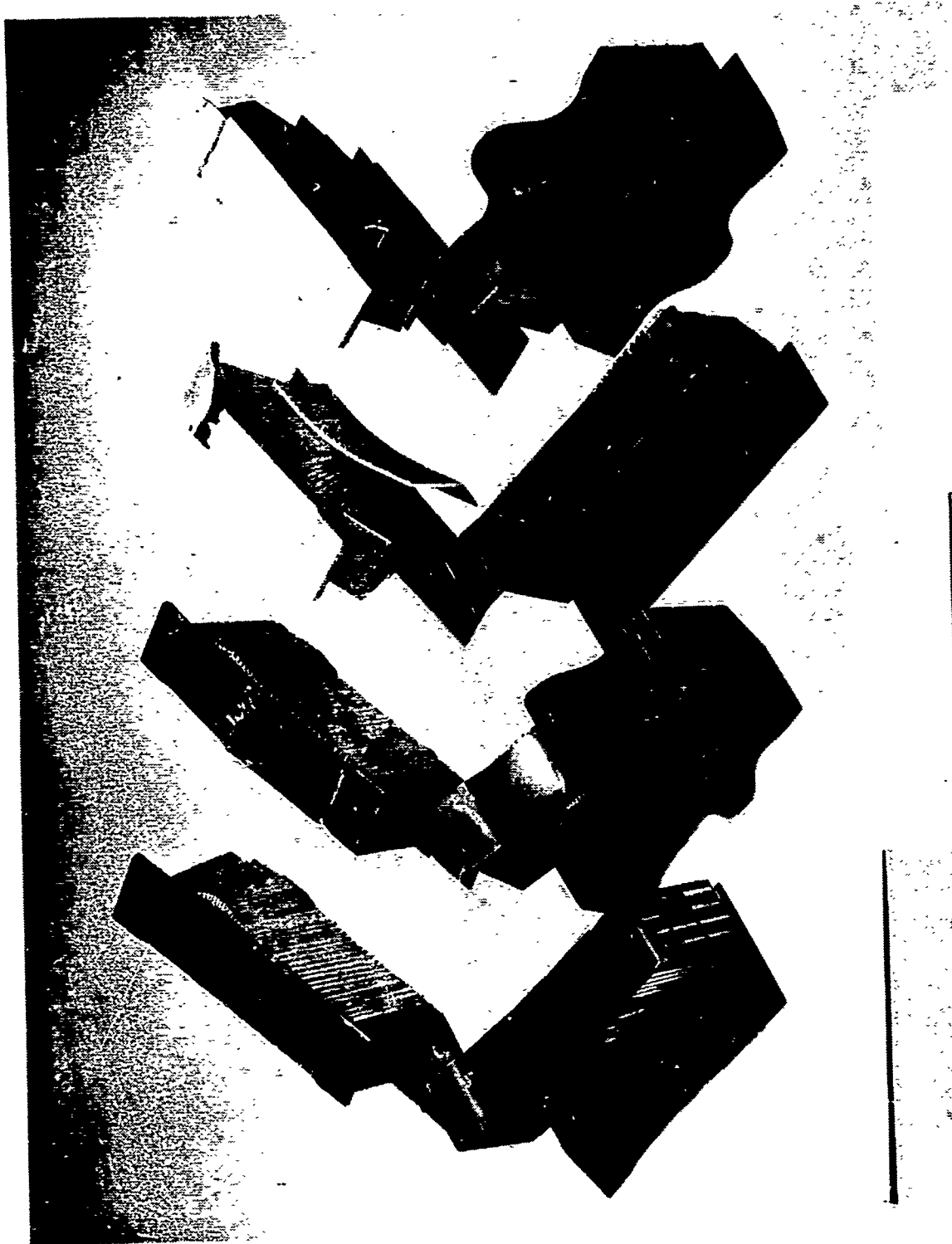


Figure 99. Failed Thermal Shock [0]₆T Compression Specimens

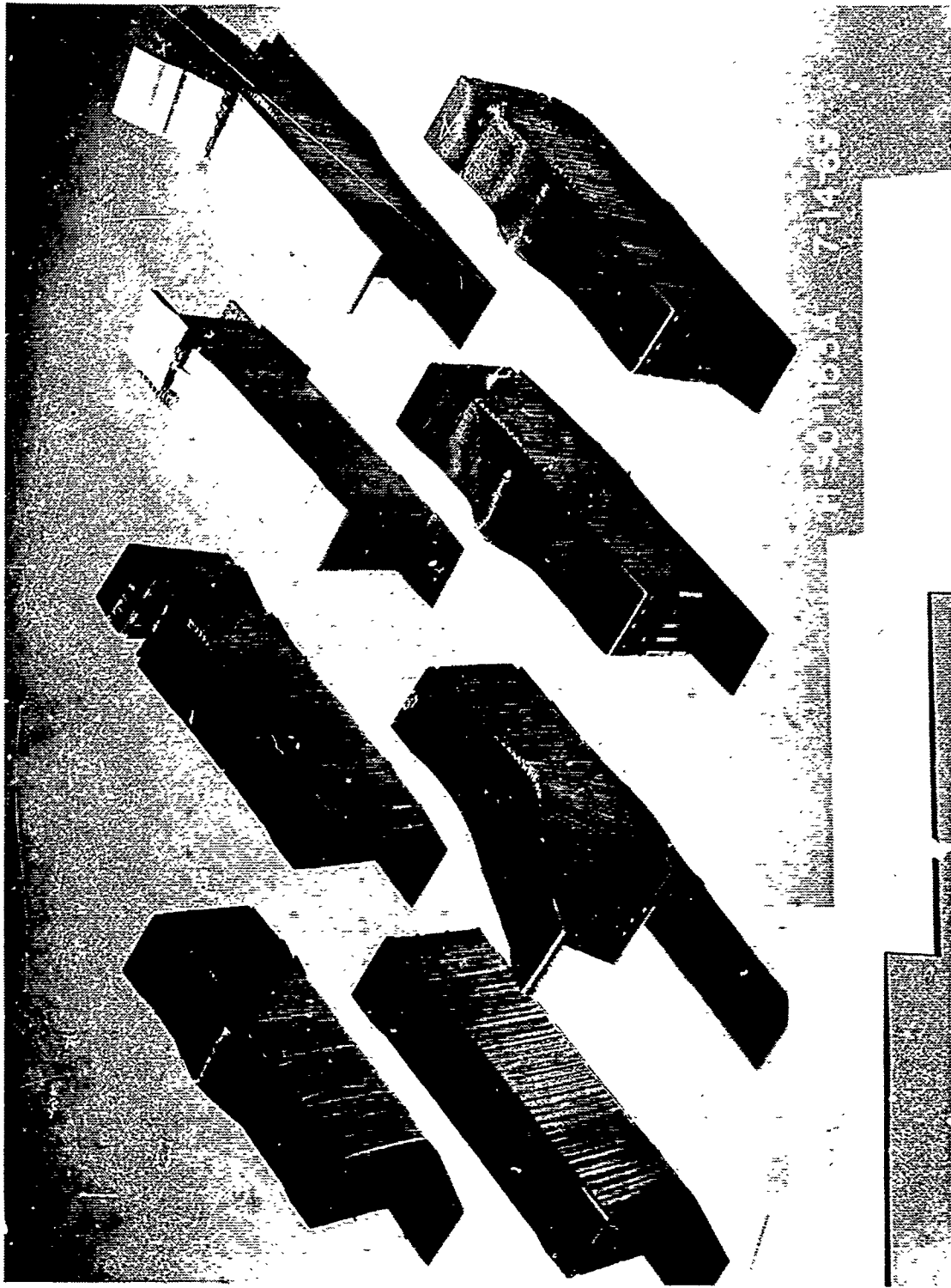


Figure 100. Failed Thermal Shock $[0/+45/0]_{2S}$ Compression Specimens

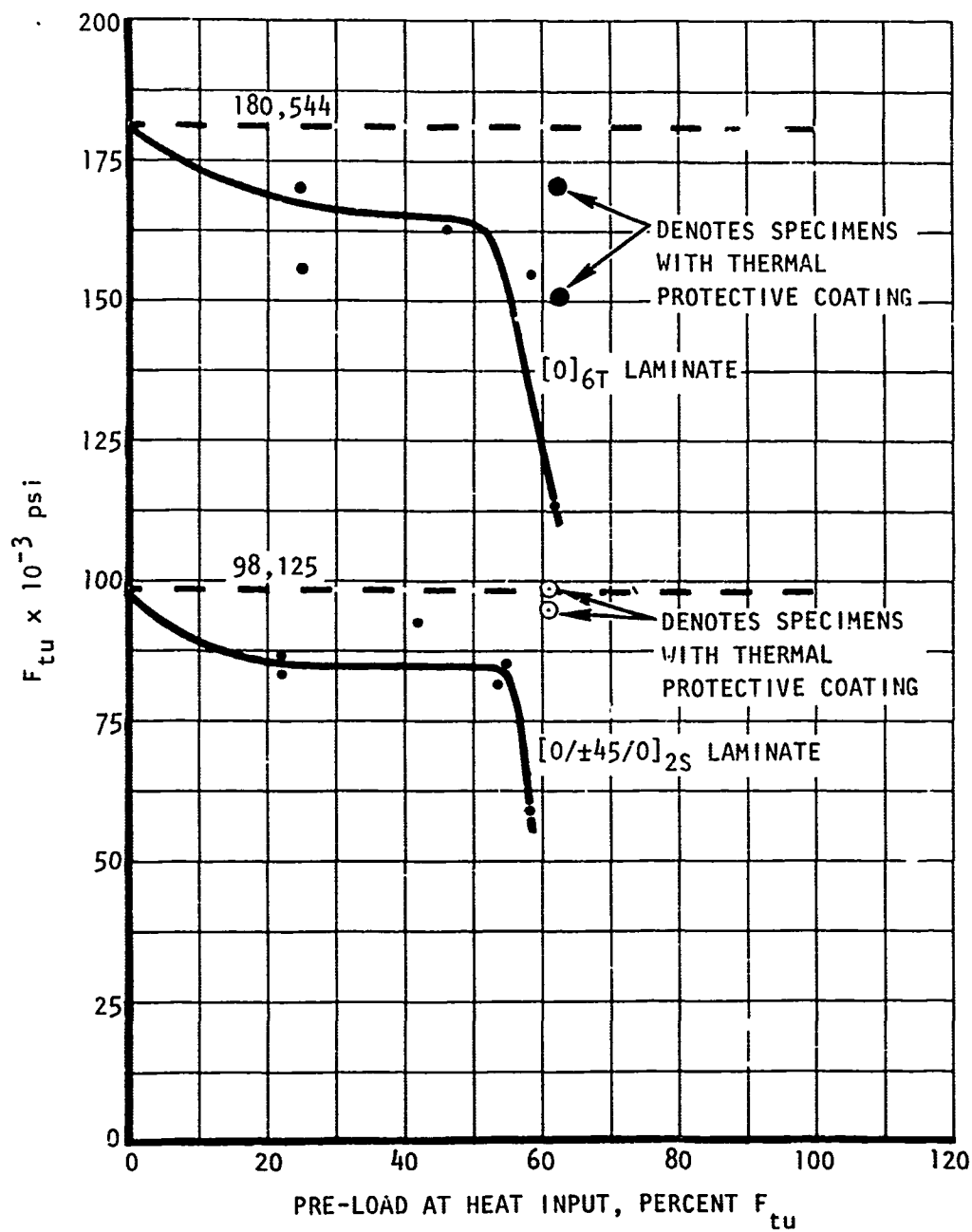


Figure 101. Degradation of Ultimate Tensile Strength vs Thermal Shock Loading

Further verification of the nondamaging effects of nuclear radiation is found in the results of other investigators. In one program (reference 3), boron/epoxy laminates were virtually unaffected by exposure to mixed radiation fields characterized by thermal and fast neutron fluxes up to 38 and 12 KTn/cm^2 , respectively, and gamma doses up to 43 G-ergs/g-cm. These radiation levels are well above crew survival limits in all but heavily shielded vehicles, so that the use of boron/epoxy composites cannot be questioned in conventional aircraft on the basis of strength degradation due to nuclear radiation. In another program (reference 4), significant degradation had not occurred at a thermal neutron flux of 30 KTn/cm^2 , confirming reference 3, but was definitely noticeable at 1 MTn/cm^2 .

SECTION V

MICROMECHANICS/MACROMECHANICS ANALYSIS

In relation to composite materials, the type of analysis which utilizes the physical and mechanical properties of the constituents, i.e., fibers, matrix, and glass cloth carrier, to predict the physical and mechanical characteristics of a single lamina is referred to as micromechanics. Macromechanics refers to the type of analysis which utilizes the physical or mechanical properties of a single lamina to predict the physical or mechanical characteristics of any laminate. This section is concerned with evaluating the accuracy of the more mundane micromechanics prediction techniques by utilizing the constituent property data generated in section IV and comparing these predicted values with experimental lamina data.

ELASTIC CONSTANTS

Table LXXVI contains the values of the elastic constants for the boron filaments, epoxy matrix, and 104 glass carrier which were used in the evaluation of the accuracy of micromechanics prediction techniques for single lamina elastic properties. The elastic properties for the matrix and 104 glass cloth were obtained from experimental data generated in this program, and the boron filament properties were obtained from the Aircraft Systems Division of the Final Draft of the Design Guide (reference 5).

For unidirectional composite materials, the "rule of mixtures" is generally used to predict the longitudinal modulus and major Poisson's ratio. This rule states that the desired property is equal to the sum of the products of the corresponding constituent property and its volume fraction; hence

$$E_L = V_f E_f + V_m E_m + V_g E_L^g \quad (1)$$

and

$$\nu_{LT} = V_f \nu_f + V_m \nu_m + V_g \nu_{LT}^g \quad (2)$$

where E_L denotes the longitudinal Young's modulus of a single lamina; ν_{LT} is the major Poisson's ratio for the lamina.

TABLE LXXVI. CONSTITUENT ELASTIC PROPERTIES

Constituent	Property	Value	
		Room Temperature	350° F
Boron filament	E_f	57.0 Msi	57.0 Msi
	ν_f	0.20	0.20
	G_f	23.75 Msi	23.75 Msi
5505 resin system	E_m^t	0.51 Msi	0.16 Msi
	E_m^c	0.53 Msi	0.17 Msi
	ν_m^t	0.31	*
	ν_m^c	0.40	*
	G_m	0.20 Msi	*
104 glass	E_L^{g***}	2.88 Msi	2.47 Msi
	E_L^{g***}	1.59 Msi	1.28 Msi
	ν_{LT}^g	0.14	0.10
	G_{LT}^g	0.93 Msi	0.50 Msi**
* Not available; ** estimated; *** tension modulus			

Figure 102 illustrates a typical unidirectional laminate whose E_L and ν_{LT} properties are predicted by equations 1 and 2.

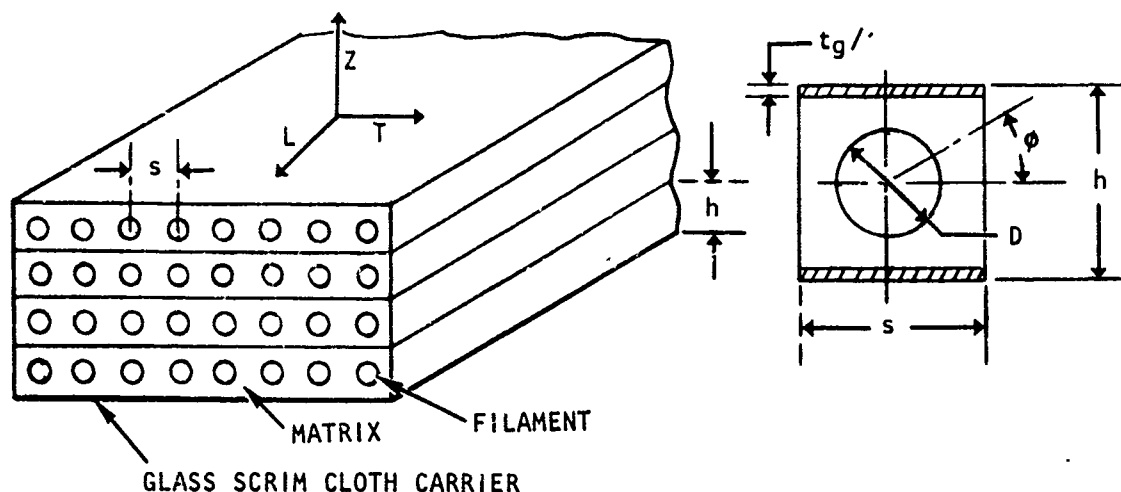


Figure 102. Typical Unidirectional Laminate and Typical Filament Unit

Figure 102 also illustrates a typical repeated filament unit, where D , s , h , and t_g denote filament diameter, filament spacing, ply thickness, and glass cloth carrier thickness, respectively. For Narmco 5505, these terms take on the following values:

$$\begin{aligned} D &= 0.004 \text{ inch} \\ s &= 0.0048 \text{ inch} \\ h &= 0.0052 \text{ inch} \\ t_g &= 0.001 \text{ inch} \end{aligned}$$

Thus, the volume fractions for the composite constituents are found to be:

$$V_f = \frac{\pi D^2}{4hs} = 0.503$$

$$V_g = \frac{t_g s}{hs} = 0.192 \quad (3)$$

$$V_m = 1 - V_f - V_g = 0.305$$

In addition to the longitudinal constants, E_L and ν_{LT} for a unidirectional composite, many micromechanics solutions have been presented for determining the transverse modulus E_T and the shear modulus G_{LT} . Most of these solutions are summarized in reference 6; however, none of these solutions accounts for the glass cloth carrier. One of the solutions (reference 7) was slightly modified to account for the carrier and is as follows:

$$E_T = \left(\frac{D}{h}\right) \int_0^{\pi/2} \bar{E}_T \cos \phi \, d\phi + E_m \left(1 - \frac{D}{h} - \frac{t_g}{h}\right) + E_T^g \left(\frac{t_g}{h}\right) \quad (4)$$

where

$$\bar{E}_T = \frac{E_f E_m [f^* E_f + (1 - f^*) E_m]}{[(1 - f^*) E_f + f^* E_m] [f^* E_f + (1 - f^*) E_m] - f^* (1 - f^*) (\nu_m E_f - \nu_f E_m)^2}$$

$$f^* = (D \cos \phi) / s$$

$$G_{LT} = \left(\frac{D}{h}\right) \int_0^{\pi/2} \bar{G}_{LT} \cos \phi \, d\phi + G_m \left(1 - \frac{D}{h} - \frac{t_g}{h}\right) + G_{LT}^g \left(\frac{t_g}{h}\right) \quad (5)$$

where

$$\bar{G}_{LT} = \frac{G_m G_f}{G_m (D \cos \phi) + G_f \left(1 - \frac{D \cos \phi}{s}\right)}$$

In reference 8, a modification to equations 4 and 5 is presented, in which the Young's moduli for the resin and scrim cloth are replaced by equivalent moduli defined by:

$$E_m^* = \frac{E_m}{(1 - \nu_m^2)} \quad (6)$$

$$(E_T^g)^* = E_T^g / \left[1 - (\nu_{LT}^g)^2 (E_T^g / E_L^g)\right]$$

The results from these relationships are compared to the values obtained from the relationships recommended in reference 9 for rectangularly packed arrays with a glass carrier, and to typical measured single-lamina elastic constants for Narmco 5505. All theoretical values were calculated by using the elastic constants listed in table LXXVII for tension loading.

TABLE LXXVII. MICROMECHANICS - TEST VERSUS THEORY

Property	Temperature	Experimental Value	Rule of Mixture	Method of Reference 7	Method of Reference 9
E_L (Msi)	RT	30.0	29.3	-	29.4*
E_T (Msi)	RT	2.60	-	2.27 2.48***	2.07** 2.32*
ν_{LT}	RT	.210	.222	-	.218
G_{LT} (Msi)	RT	1.00	-	0.88	0.82
<p>* E_L^g was used to calculate this number.</p> <p>** E_T^g was used to calculate this number.</p> <p>*** Method of reference 8.</p>					

The correlation of prediction methods with test data in table LXXVII is reasonably good and, as such, indicates that relatively simple closed-formed micromechanics procedures can be utilized to predict elastic constants for single laminae of filamentary composite materials.

THERMAL EXPANSION MICROMECHANICS

The thermal expansion investigations consisted of micromechanical and macromechanical phases. The micromechanical portion involves predictions of expansion coefficients for single, unidirectional, composite laminae. The second part takes a macromechanical approach to describe the behavior of multi-ply laminates subjected to uniform temperature changes.

Thermal expansion coefficients and thermal stresses are calculated on the basis of an a priori knowledge of the mechanical and thermal response characteristics of each ply. A comparison of the predicted and experimental expansion coefficients for a boron/epoxy composite system is presented.

EXPANSION COEFFICIENTS

We first consider a single ply consisting of regularly spaced, unidirectional fibers embedded in a matrix material. This model is shown in figure 103.

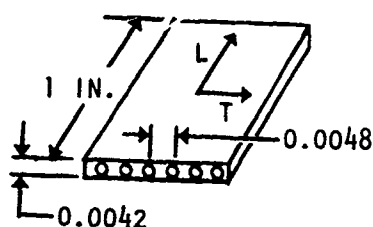


Figure 103. Model of Single Lamina Element

It is assumed that both fibers and matrix materials are homogeneous, isotropic, and linearly elastic. It is further assumed that the fiber and matrix are firmly bonded together and that there are no voids in the composite.

The longitudinal coefficient of thermal expansion, α_L , is obtained by enforcing the conditions of force equilibrium and compatibility in the longitudinal direction. Since there are no external forces applied to the composite layer, the equation expressing force equilibrium is given by:

$$\sigma_f \bar{V}_f + \sigma_m (1 - \bar{V}_f) = 0 \quad (7)$$

where σ denotes normal stress, the subscripts f and m denote filament and matrix, respectively, and \bar{V}_f is the filament volume fraction.

The corresponding compatibility condition is

$$\epsilon_L = \epsilon_f = \epsilon_m \quad (8)$$

where ϵ denotes strain and L, f, and m denote total longitudinal ply, longitudinal filament, and longitudinal matrix strains, respectively.

Since both fiber and matrix were assumed to be isotropic, elastic materials, then stress-strain relations are:

$$\epsilon_f = \frac{\sigma_f}{E_f} + \alpha_f \Delta T = \epsilon_L \quad (9)$$

$$\epsilon_m = \frac{\sigma_m}{E_m} + \alpha_m \Delta T = \epsilon_L \quad (10)$$

Solving equations 9 and 10 for the stress components and then substituting equation 7 yields

$$\epsilon_L = \alpha_f \left(\frac{E_f}{E_L} \right) \Delta T \bar{V}_f + \alpha_m \left(\frac{E_m}{E_L} \right) \left(1 - \bar{V}_f \right) \Delta T \quad (11)$$

where:

$$E_L = \bar{V}_f E_f + \left(1 - \bar{V}_f \right) E_m \quad (12)$$

Then, from equation 11, the longitudinal coefficient of thermal expansion is given by:

$$\bar{\alpha}_L = \frac{\epsilon_L}{\Delta T} = \alpha_f \left(\frac{E_f}{E_L} \right) \bar{V}_f + \alpha_m \left(\frac{E_m}{E_L} \right) \left(1 - \bar{V}_f \right) \quad (13)$$

Generally, derivation of the transverse coefficient of thermal expansion is not as simple as that for α_L . The solution for a rectangular array of cylindrical fibers was presented in reference 10. The approach taken accounts for the shape of the fibers and, consequently, the expression for α_T includes rather complex integrals. However, an approximate solution, which is shown to be quite close to the exact solution is also presented. The approximate expression for α_T is given in equation 14.

$$\bar{\alpha}_T = \left(1/\bar{E}_T \right) \left[\alpha_o E_o \beta + \alpha_m E_m (1 - \beta) \right] \quad (14)$$

where $\alpha_o = \alpha_m (1 - 2\beta) + 2\beta\alpha_f - \nu_m (\alpha_f - \alpha_m) (1 - 2\beta)$

$$E_o = \frac{E_m E_f}{E_f (1 - 2\beta) + 2E_m \beta}$$

$$\bar{E}_T = E_o \beta + E_m (1 - \beta)$$

$$\beta = \sqrt{\frac{\bar{V}_f}{\pi}} \text{ and } \nu_m = \text{Poisson's ratio of the matrix}$$

A much simpler expression results for $\bar{\alpha}_T$ if it is assumed that the rule of mixtures is applicable. The transverse coefficient of expansion is then given by:

$$\bar{\alpha}_T = \alpha_m (1 - \bar{V}_f) + \alpha_f \bar{V}_f \quad (15)$$

Equations 14 and 15 were used to calculate α_T for a boron/epoxy composite. Constituent properties used in these calculation are given in table LXXVI. The predicted values for α_T are presented in figure 105 as a function of filament volume fraction. There is not much difference between the two sets of values for fiber volume fractions up to about 50 percent (maximum deviation of approximately 10 percent between predicted values). The fiber volume fraction of the boron/epoxy layer of the boron/epoxy-scrim prepreg tape is 62.3 percent. For this fiber volume fraction, the law of mixtures predicts an $\bar{\alpha}_T$ of 11.8 $\mu\text{in./in./}^\circ\text{F}$, while the method of reference 10 predicts 8.8 $\mu\text{in./in./}^\circ\text{F}$.

The boron/epoxy prepregs currently being used for structural laminates have a woven glass scrim backing (figure 104). The presence of the glass scrim modifies the thermal expansion behavior of the boron/epoxy composite to some extent. Two micromechanical approaches were taken to include the effects of the scrim.

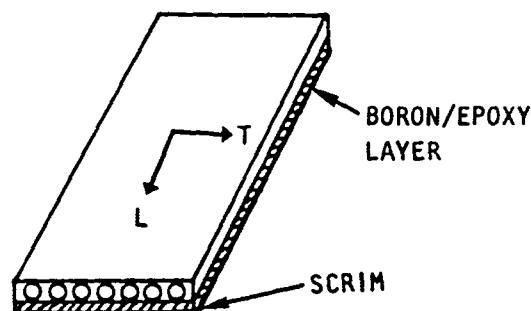


Figure 104. Model of Single Lamina Element with Scrim Cloth

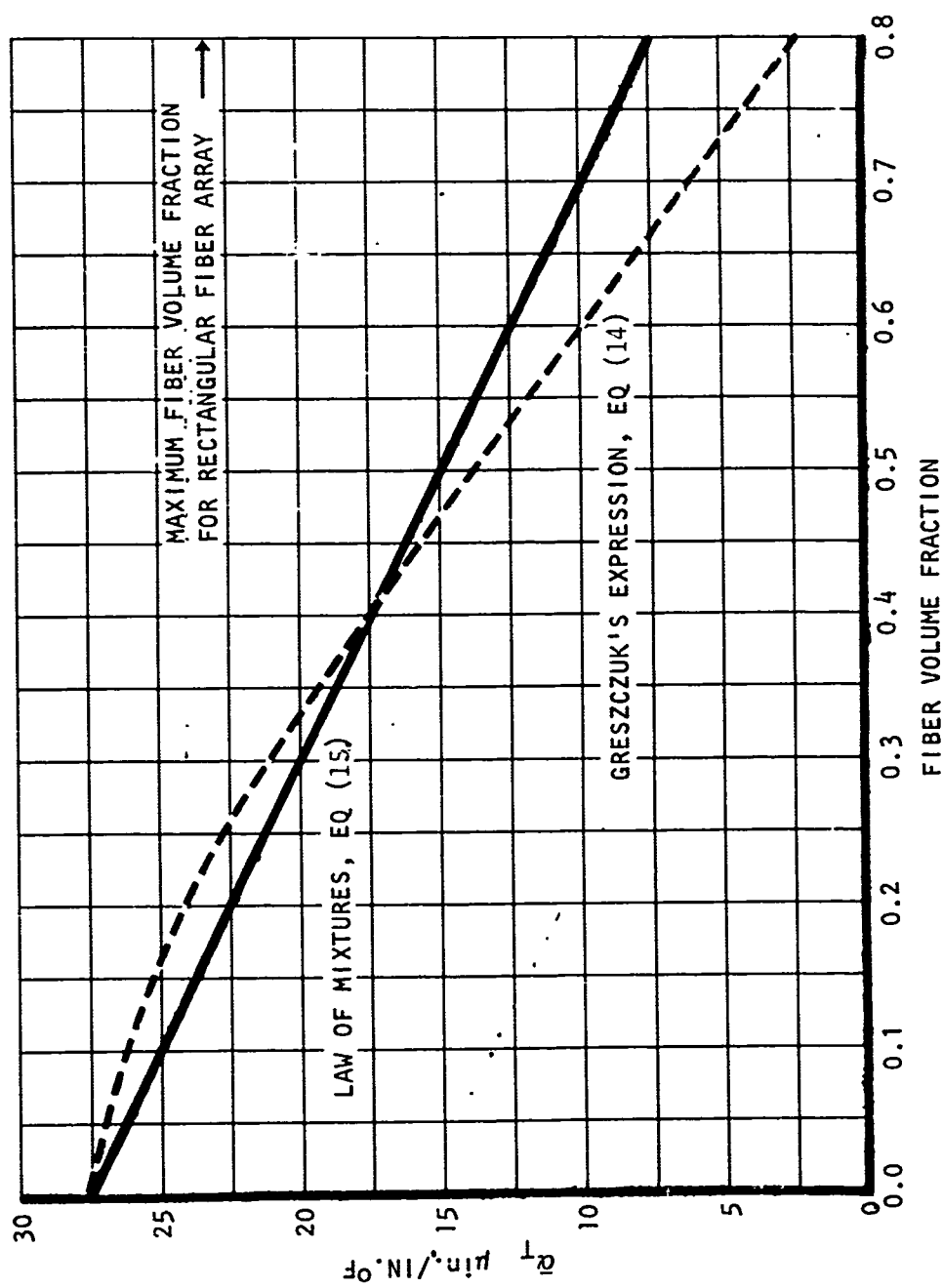


Figure 105. $\bar{\alpha}_T$ - Transverse Coefficient of Thermal Expansion for Boron/Epoxy Ply (No Scrim)

The first of these approaches provides the simplest expression for α_T by assuming that the rule of mixtures is applicable. Although this assumption is conceptually fallacious, it is a reasonable starting point since the scrim comprises a very small fraction of the total volume. On the basis of this assumption, α_T is given by:

$$\alpha_T = V_f \alpha_f + V_m \alpha_m + V_g \alpha_T^g \quad (16)$$

The longitudinal coefficient of expansion is calculated on the basis that the boron/epoxy layer is in parallel with the glass scrim layer. This model is shown schematically in figure 105.

The conditions of force equilibrium and strain compatibility in the L-direction are enforced to determine α_L . The force equilibrium equation (no externally applied forces) is given by:

$$\bar{\sigma}_L k' + \sigma_L^g (1 - k') = 0 \quad (17)$$

where:

$$k' = V_f + V_m \quad (18)$$

The compatibility equation is:

$$\bar{\epsilon}_L = \epsilon_L^g = \epsilon_L \quad (19)$$

Then, assuming that no transverse stresses develop, the stress-strain relations for the boron/epoxy layer and glass scrim are:

$$\begin{aligned} \bar{\epsilon}_L &= (\bar{\sigma}_L / E_L) + \bar{\alpha}_L \Delta T \\ \epsilon_L^g &= (\sigma_L^g / E_L^g) + \alpha_L^g \Delta T \end{aligned} \quad (20)$$

Combining equations 19 and 20 yields:

$$\begin{aligned} \bar{\sigma}_L &= \bar{E}_L \epsilon_L - \bar{\alpha}_L \bar{E}_L \Delta T \\ \sigma_L^g &= E_L^g \epsilon_L - \alpha_L^g E_L^g \Delta T \end{aligned} \quad (21)$$

Then, substituting equations 21 into 17 produces:

$$k' \left(\bar{E}_L \epsilon_L - \bar{\alpha}_L \bar{E}_L \Delta T \right) + (1 - k') \left(E_L^g \epsilon_L - \alpha_L^g E_L^g \Delta T \right) = 0$$

(22)

or

$$\alpha_L = \frac{\epsilon_L}{\Delta T} = \bar{\alpha}_L \left(\bar{E}_L / E_L \right) k' + \alpha_L^g \left(E_L^g / E_L \right) (1 - k')$$

where:

$$E_L = k' \bar{E}_L + (1 - k') E_L^g$$

A more conceptually sound method for calculating α_T does not employ the arbitrary assumption or the rule of mixtures. This approach considers the boron/epoxy layer to be in parallel with the scrim in both the L and T directions. In other words, the expansion of two bonded orthotropic thin layers is considered. The macroscopic approach to this problem will be discussed later. It will be assumed that the properties of the two layers are known, either from micromechanical considerations or from experiment. An approximate micromechanical approach will be presented here for comparison with equation 16 and the macromechanical approach to be presented later.

We proceed to calculate α_T in a manner similar to that employed to determine α_L of equation 22. The equations of equilibrium of compatibility in the T-direction are:

$$\bar{\alpha}_T k' + \alpha_T^g (1 - k') = 0$$

(23)

and

$$\bar{\epsilon}_T = \epsilon_T^g = \epsilon_T$$

(24)

Assuming no longitudinal stresses develop for uniform temperature change, the stress-strain relations for the two layers are:

$$\bar{\epsilon}_T = \left(\bar{\sigma}_T / \bar{E}_T \right) + \bar{\alpha}_T \Delta T$$

$$\epsilon_T^g = \left(\sigma_T^g / E_T^g \right) + \alpha_T^g \Delta T$$

(25)

Combining equations 24 and 25 yields:

$$\begin{aligned}\bar{\sigma}_T &= \bar{E}_T \epsilon_T - \bar{\alpha}_T \bar{E}_T \Delta T \\ \sigma_T^g &= E_T^g \epsilon_T - \alpha_T^g E_T^g \Delta T\end{aligned}\tag{26}$$

Substituting equations 26 into 23 results in:

$$\begin{aligned}k' \left(\bar{E}_T \epsilon_T - \bar{\alpha}_T \bar{E}_T \Delta T \right) + (1 - k') \left(E_T^g \epsilon_T - \alpha_T^g E_T^g \Delta T \right) &= 0 \\ \text{or} \\ \alpha_T = \frac{\epsilon_T}{\Delta T} = \bar{\alpha}_T \left(\bar{E}_T / E_T \right) k' + \alpha_T^g \left(E_T^g / E_T \right) (1 - k')\end{aligned}\tag{27}$$

where:

$$E_T = k' \bar{E}_T + (1 - k') E_T^g$$

The longitudinal expansion coefficient is identical to that obtained for the previously considered case. Consequently, equation 22 provides the estimated longitudinal expansion coefficient by replacing the subscript T with L.

A summary of expressions to be used in numerical computations is presented in table LXXVIII.

TABLE LXXVIII. SUMMARY OF EXPRESSIONS

I. Expansion Coefficients for Boron/Epoxy Lamina (without glass cloth carrier) - $\bar{\alpha}_T, \bar{\alpha}_L$

$$\bar{\alpha}_T = \alpha_m (1 - \bar{V}_f) + \alpha_f \bar{V}_f$$

$$\bar{\alpha}_L = \alpha_f \left(E_f / \bar{E}_L \right) \bar{V}_f + \alpha_m \left(E_m / \bar{E}_L \right) (1 - \bar{V}_f)$$

$$\bar{E}_L = \bar{V}_f E_f + (1 - \bar{V}_f) E_m$$

TABLE LXXVIII. SUMMARY OF EXPRESSIONS (CONCLUDED)

II. Law of Mixtures for α_T , Boron/Epoxy Scrim Lamina

$$\alpha_T = V_f \alpha_f + V_m \alpha_m + V_g \alpha_T^g$$

$$\alpha_L = \bar{\alpha}_L \left(\bar{E}_L / E_L \right) k' + \alpha_L^g \left(E_L^g / E_L \right) (1 - k')$$

$$E_L = k' \bar{E}_L + (1 - k') E_L^g$$

$$k' = V_f + V_m, \quad V_g = 1 - k'$$

III. Boron/Epoxy in Parallel With Scrim

$$\alpha_T = \bar{\alpha}_T \left(\bar{E}_T / E_T \right) k' + \alpha_T^g \left(E_T^g / E_T \right) (1 - k')$$

$$E_T = k' \bar{E}_T + (1 - k') E_T^g$$

$$\alpha_L = \bar{\alpha}_L \left(\bar{E}_L / E_L \right) k' + \alpha_L^g \left(E_L^g / E_L \right) (1 - k')$$

$$E_L = k' \bar{E}_L + (1 - k') E_L^g$$

CORRELATION WITH EXPERIMENT

The micromechanical expressions derived for α_T and α_L were used to predict these quantities for comparison with experimental values. Table LXXIX presents the constituent properties for these calculations as obtained from this report and reference 11.

TABLE LXXIX. CONSTITUENT PROPERTIES

Property	RT	260° F	350° F
$\alpha_f, \mu \text{ in./in./}^\circ\text{F}$	2.7	2.7	2.7
$\alpha_m, \mu \text{ in./in./}^\circ\text{F}$	27.4	33.3	38.0
$\alpha_T^g, \mu \text{ in./in./}^\circ\text{F}$	9.5	9.3	10.6
$\alpha_L^g, \mu \text{ in./in./}^\circ\text{F}$	6.2	6.2	7.0
E_f, Msi	57.0	57.0	57.0
E_m, Msi	0.51	-	0.16
E_T^g, Msi	1.59	1.4	1.28
E_L^g, Msi	2.88	2.6	2.47

Experimental values of the boron/epoxy composite with glass scrim backing are given in table LXXX (reference 12).

TABLE LXXX. BORON/EPOXY COMPOSITE PROPERTIES
(INCLUDING SCRIM CLOTH)

Property	RT	260° F	350° F
$\alpha_L, \mu \text{ in./in./}^\circ\text{F}$	2.32	2.53	2.83
$\alpha_T, \mu \text{ in./in./}^\circ\text{F}$	10.67	14.98	13.98

The volume fractions of the constituents for the Narmco 5505 system are $V_g = 0.192$, $V_f = 0.503$, $V_m = 0.305$. In the boron/epoxy layer, $\bar{V}_f = 0.623$, $\bar{V}_m = 0.377$. The values for α_L and α_T calculated from the expressions summarized in table LXXVIII are presented in table LXXXI.

TABLE LXXXI. CALCULATED EXPANSION COEFFICIENTS

Property	Expressions Used	RT	260° F	350° F
α_L	II	2.88	-	2.82
	III	2.88	-	2.82
α_T	II	11.55	13.3	15.00
	III	11.67	-	-

From this table we can see that there is not much difference in the results obtained by the two methods. The probable reason for this is the fact that the scrim represents a very small percentage of the boron/epoxy-scrim composite and has only little effect on the total behavior. In view of this, there is little justification for using the more complicated expressions III in preference to the simpler law of mixture expressions II.

THERMAL EXPANSION - MACROMECHANICS

Once the elastic and thermal response characteristics for each ply have been determined, the thermal response for an N-ply laminate can be predicted with the use of micromechanics. In this subsection we consider that the ply coefficients of thermal expansion α_L , α_T , α_{LT} are known from testing or the previous micromechanics subsection.

The thermoelastic stress-strain relationship for the i^{th} ply of the laminate for a state of plane-stress, i.e., the stress components normal to the LT plane are taken to be zero, is given as:

$$\begin{Bmatrix} \sigma_L \\ \sigma_T \\ \sigma_{LT} \end{Bmatrix}_i = \begin{bmatrix} T_{11} & T_{12} & 0 \\ T_{12} & T_{22} & 0 \\ 0 & 0 & 2T_{33} \end{bmatrix}_i \begin{Bmatrix} \epsilon_L - \alpha_L \Delta T \\ \epsilon_T - \alpha_T \Delta T \\ \epsilon_{LT} \end{Bmatrix}_i \quad (28)$$

where:

$$\begin{aligned} T_{11} &= E_L / (1 - \nu_{LT} \nu_{TL}) = T_{22} E_T / E_L \\ T_{12} &= \nu_{TL} T_{11} = \nu_{LT} T_{22} \\ T_{33} &= G_{LT} \end{aligned}$$

With the use of appropriate coordinate transformations and the foregoing relations, the coefficients of thermal expansion for the N-ply laminate shown in figure 106 are shown in reference 13 to be:

$$\{\alpha^C\} = \begin{Bmatrix} \alpha_x^C \\ \alpha_y^C \\ \alpha_{xy}^C \end{Bmatrix} = [B]^{-1} \{C\} \quad (29)$$

where the terms on the right side of equation 29 are defined in reference 13, and $\{\alpha^C\}$ are the coefficients of thermal expansion for the laminate. The coefficient α_{xy}^C is associated with a shear mode of thermal distortion and takes on the value of zero whenever the laminate is balanced in the sense that it is composed only of sets of $\pm\theta$ plies. The general picture of thermal distortion of an N-ply laminate due to a uniform temperature change of ΔT is also shown in figure 106.

The equations developed in reference 13 for multi-ply laminates were programed for an IBM 360 computer for application to boron/epoxy laminates. The computer program, designated as AC-40, requires a nominal number of input data for each case and is described in full in reference 13.

CURVES FOR COEFFICIENTS OF THERMAL EXPANSION

In order to assist the designer in predicting the coefficients of thermal expansion for laminates, i.e., α_x^C , α_y^C , α_{xy}^C , a curve is presented for laminates of the type $[0_{n1}/\pm 45_{n2}/90_{n3}]_C$, where the designer only needs to know the relative percentages of the plies at 0° , $\pm 45^\circ$, and 90° ,

where n_1 = number of plies at 0°
 $2n_2$ = number of plies at $\pm 45^\circ$
 n_3 = number of plies at 90°

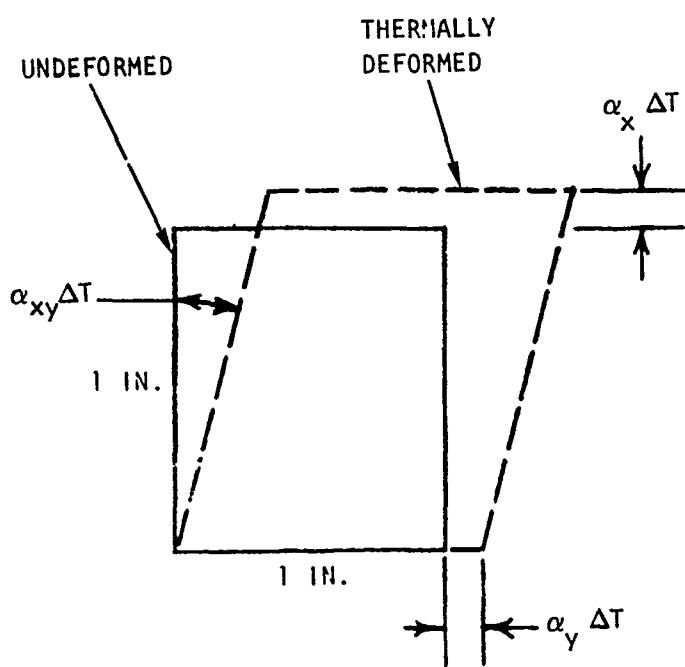
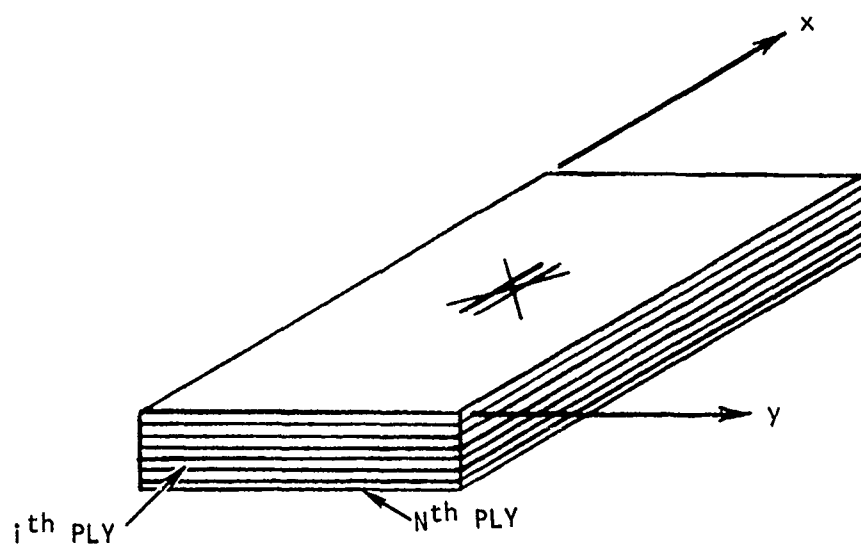


Figure 106. Typical n-Ply Laminate and Thermal Distortion

This design curve is presented as figure 107 and is for finding α_x^C . If α_y^C is desired, it can be found by reading the curve for α_x^C after interchanging the "% at 0°" and "% at 90°" labels. Further, for this type of laminate, $\alpha_{xy}^C = 0$. Similarly, curves for other laminate families can be developed with the utilization of AC-40.

CORRELATION WITH EXISTING ANGLEPLY DATA

Some coefficient of thermal expansion data for $[0_2/\pm 45]_C$ and $[0/\pm 60]_C$ laminates are available from reference 12 and are compared to values predicted by AC-40. The results of this comparison, shown in table LXXXII indicate that the prediction technique developed on the previous pages is valid at room temperature. However, caution should be used at elevated temperatures because of the nonlinearity of the unidirectional transverse α_T .

TABLE LXXXII. COMPARISON OF PREDICTED VALUES AND TEST DATA FOR COEFFICIENTS OF THERMAL EXPANSION AT ROOM TEMPERATURE

$[0_2/\pm 45]_C$				$[0/\pm 60]_C$			
α_x^C $\mu \text{ in./in./}^\circ\text{F}$		α_y^C $\mu \text{ in./in./}^\circ\text{F}$		α_x^C $\mu \text{ in./in./}^\circ\text{F}$		α_y^C $\mu \text{ in./in./}^\circ\text{F}$	
Pred	Test	Pred	Test	Pred	Test	Pred	Test
2.36	2.60	7.75	6.10	3.10	3.25	4.85	3.3

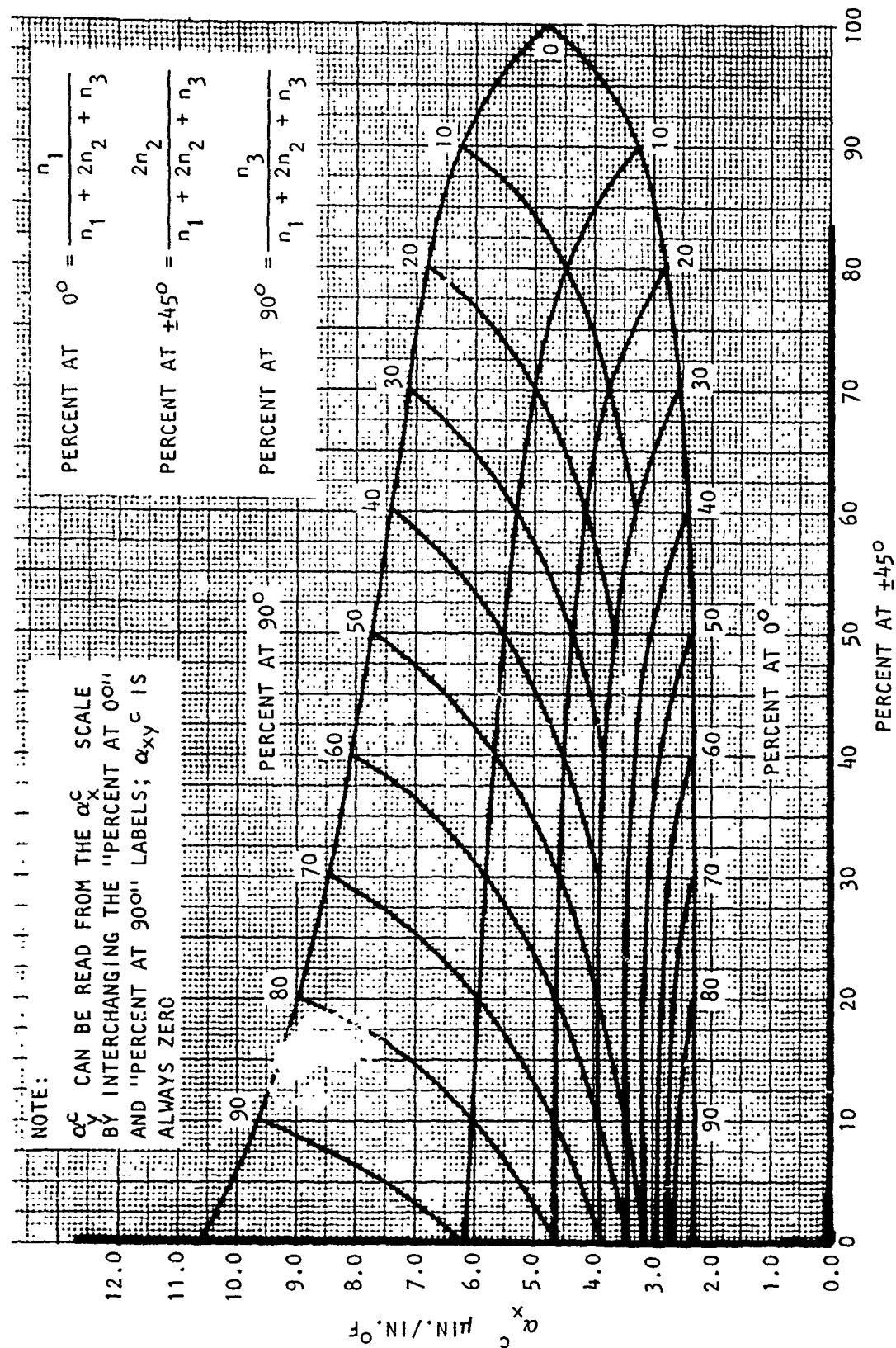


Figure 107. Longitudinal Coefficient of Thermal Expansion for Laminates of the Type $[0_{n_1}/\pm 45_{n_2}/90_{n_3}]_C$ at Room Temperature

APPENDIX I

PROCUREMENT SPECIFICATION

ADVANCED COMPOSITE MATERIAL - BORON/EPOXY PREPREG

(NR Specification ST0130LB0004)

PREPARED BY R. MEADOWS APPROVALS <i>H. K. Dimmock</i>	CODE IDENT. NO. 43999 LOS ANGELES DIVISION NORTH AMERICAN ROCKWELL CORPORATION <h2 style="margin: 0;">SPECIFICATION</h2>	NUMBER ST0130LB0004 TYPE MATERIAL DATE 4-26-69 SUPERSEDES SPEC. DATED: 20 February 1969 REV. LTR. A			
TITLE ADVANCED COMPOSITE MATERIAL - BORON EPOXY PREPREG					
<div style="text-align: center;"> <ol style="list-style-type: none"> 1. SCOPE 2. APPLICABLE DOCUMENTS 3. REQUIREMENTS 4. QUALITY ASSURANCE 5. PREPARATION FOR DELIVERY 6. NOTES </div>					
<h3>REVISIONS</h3>					
REV.	DATE	REV. BY	PAGES AFFECTED	REMARKS	APPROVED

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AEROSPACE AND SYSTEMS GROUP

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1. SCOPE

1.1 This specification establishes the requirements for thermosetting resin treated, parallel in-plane, collimated, continuous monofilament boron fiber preimpregnated material.

1.2 Classification.

1.2.1 Resin Type.— The impregnating resin shall be classified as follows:

Type	Description of Impregnating Resin
I	General Purpose (200° F max.; continuous exposure up to 10,000 hours)
II	Heat Resistant (350° F max.; continuous exposure up to 1,000 hours)
III (Future)	High Heat Resistant (600° F max.; continuous exposure up to 1,000 hours)

1.2.2 Impregnated Boron Filament.— The impregnated boron filament shall be classified as follows:

Class

- 1 A nonintegral composite of boron filaments supported and oriented on a woven glass fabric, and impregnated with an applicable thermosetting resin.
- 2 An unsupported composite of boron filaments impregnated with an applicable thermosetting resin.

2. APPLICABLE DOCUMENTS

2.1 Documents.— The latest issues of the following documents form a part of this specification to the extent specified herein:

SPECIFICATIONS

Military

MIL-R-9300 Resin, Epoxy, Low Pressure Laminating

North American Rockwell Corporation

ST0105LAOC07 Advanced Composites-Fabrication of Parts or Components
Utilizing Boron-Epoxy Prepreg

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American Society for Testing and Materials

ASTM D579 Standard Specifications and Methods of Test for Woven Glass Fabrics

STANDARDS

Federal

Federal Test Plastics: Method of Testing
Method Std.No.406

Military

MIL-STD-414 Sampling Procedures and Tables for Inspection by Variables for Percent Defective

Society for Plastics Industry

SPI-Prepreg-1 Resin and Volatile Content of Preimpregnated Inorganic Reinforcements

3. REQUIREMENTS

3.1 General.— Preimpregnated materials covered by this specification shall consist of parallel in-plane, collimated, continuous length boron filaments, supported, class 1, or unsupported, class 2, and impregnated with the applicable thermosetting resin as specified. They shall be capable of being molded, using low pressure laminating methods (under 100 psi), to produce a cured molding having properties described in this specification.

3.2 Materials Procured by the Supplier.—

3.2.1 Impregnating Resin.— The resin used for types I and II shall conform to the general requirements of MIL-R-9300. The resin shall be free of foreign materials, noncorrosive to metals and shall be capable of being molded, using low pressure laminating methods, to a fully thermoset state and meet the requirements of this specification.

3.2.2 Boron Filament.—

a. Material.— The boron filament material supplied to the tape processor shall meet the requirements shown in table I.

Table I
BORON FILAMENT PROPERTIES

Property	Requirement
Tensile Strength, min. avg., psi	450,000
Modulus of Elasticity, Tension min. avg., psi	55 x 10 ⁶
Diameter, Inches	0.0039 to 0.0041
Density, Maximum lbs/in. ³	0.095

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- b. Splices. - Splicing of boron filaments shall be permitted in accordance with the following requirements:

Method - 1 inch to 2 inches overlap splice with uniform resin application.

Heat Requirements - Types I and II material splices shall be capable of withstanding a minimum of 200 gram tensile load at 400°F for not less than 10 minutes and must not emit volatiles at temperatures up to 375° F.

Conformability - Splices having any indication of breaks or splits after being wound on the shipping spools by the filament producer shall be cause for rejection.

Frequency - Average distance between splices shall be a minimum of 1000 ft.

Labeling - All splices shall be marked by inserting a black strip of paper under the splice.

- c. Filament Spool Requirements. -

Spool Diameter - The boron filaments shall be supplied on spools of a diameter not less than 8 inches.

Winding Tension - Boron filaments shall be wound under uniform tension on the shipping spools.

Winding Pattern - Filaments shall be level when wound on the spools with a minimum spacing between adjacent filaments, with no overlapping or crossovers of filaments.

Liner Interleave - Filaments shall be wound with a paper liner interleave inserted at the end of each level wind with no overlapping or crossovers of filaments permitted before the liner is inserted.

Filament Length per Spool - Each spool shall contain 20,000 ft. \pm 10 percent of boron filament material.

3.2.3 Glass Fabric Carrier. - When specifying class 1, the glass fabric carrier shall conform to requirements of ASTM D579 type 58 (Industry Style 104) fabric with a 1100 soft finish. These supporting materials shall be capable of holding the collimated boron filaments in their fixed positions while in storage, during shipping and when handling during layup operations. The warp of the carrier cloth shall be parallel to the length of the boron filament of the prepreg.

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3.3 Materials Procured by North American Rockwell Corporation (NR).— Boron filament reinforced uncured plastic preimpregnated material, class 1 and class 2 shall consist of collimated, parallel in-plane boron filaments impregnated with thermosetting resin (see 3.2.1) and shall be supplied by the linear foot in 3-inch widths for class 1 and 1/8-inch widths for class 2.

- a. Boron filaments shall be completely wetted by the resin.
- b. Preimpregnated material shall have 206 to 214 filaments for each 1.000-inch width of material. The minimum number of feet of class 1 material, per pound of filament supplied, shall be based on the number of filaments per inch of width as stated below. A maximum loss of 10 percent shall be allowed for processing.

<u>Fibers per 1 inch of Tape</u>	<u>Feet of Delivered 3 inch Wide (class 1) Prepreg per Pound of Bare Filament, minimum</u>
206	102
208	101
210	100
212	99
214	98

- c. All filaments shall be collimated and parallel to the center line of the prepreg within an angle of 15 minutes.
- d. Filaments shall not be crimped.
- e. There shall be no cured resin particles in the material.
- f. Prepreg shall be free of all parting agents or any other foreign material, and shall be of uniform natural color.
- g. The physical properties of the uncured prepreg material be in accordance with the requirements shown in table II.

Table II
UNCURED PREPREG, PHYSICAL PROPERTIES

<u>Property</u>	<u>Requirement</u>
Volatile content, percent by weight	2 % max.
Resin content, percent by weight	29 - 34
Tack	Shall adhere to a steel plate when held in a vertical position.
Gel Time *	To be defined later

*NOTE: Such to produce a ply thickness of 0.0051 to 0.0054 inch when cured per ST0105LA0007.

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3.3.1 Boron Filament Spacing.— Spacing between adjacent filaments shall be 0.012 inch maximum and 0.0002 inch minimum (see 4.23); they shall not touch each other. Not more than 3 percent of the quantity of tape inspected may deviate from the above requirements. Boron filaments shall not cross over any other filament.

NOTE: Average filament spacing is 0.0008 inch.

3.3.2 Boron Filament Splices.— No more than 4 filament splices shall occur in any 12 inch length of class 1 prepreg. No more than 3 such groups of splices per 100 feet of tape shall be permitted.

3.3.3 Prepreg Width.— Prepreg material shall be furnished in 3 inch widths for class 1 and 1/8 inch widths for class 2 unless otherwise specified in purchase order. Widths shall be held to within $\pm .031$ inch.

3.3.4 Prepreg Length.— Prepreg length per roll shall be 250-400 feet except the last roll of a batch which shall exceed 25 feet.

3.3.5 Prepreg Uniformity.— Each batch of prepreg material shall be of uniform quality throughout. Any section of prepreg material which does not meet the requirements of this specification shall not be removed from a continuous length of material. Lineal footage of rejected material shall be itemized on the inspection tag attached to the roll of prepreg and shall not be included in the specified length of prepreg material. Maximum acceptable waviness of any 24 inch length shall be .030 inch from the edge.

3.3.6 Storage Life (Shelf Life).— The prepreg material shall meet the requirements of this specification after storage of 6 months at temperatures not exceeding 60° F or a minimum of 15 days storage at 75° F maximum.

3.3.7 Workmanship.— Prepreg material furnished to this specification shall be of quality workmanship and shall be free of all impurities and defects which could adversely affect its performance. Visible indication of dry spots, voids, crossed or broken fibers, irregular carrier or incomplete impregnation shall be marked by inserts and shall be cause for rejection only if the total length of such areas exceeds 2 percent of the total tape length of the roll. Unrolled tape shall lie flat.

3.4 Cured Prepreg.— Mechanical properties of cured, laminated prepreg shall conform to requirements listed in tables III and IV when fabricated in accordance with ST0105LA0007 and tested in accordance with 4.30.

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Table III
REQUIREMENTS FOR MECHANICAL PROPERTIES OF CURED LAMINATES

Test	Temperature, ° F	Minimum Ultimate Values, Ksi		
		Type I	Type II	Type III
Flexure, longitudinal	RT	225	225	
	270	-	195	
	350	-	170	
Flexure, transverse	RT	10.0	13.0	
	270	-	10.0	
	350	-	8.0	
Horizontal Shear	RT	13.0	13.0	
	270	-	7.0	
	350	-	5.0	

Table IV
SANDWICH FACE TENSION
TEST REQUIREMENTS FOR TYPE II CURED LAMINATES

Filament Orientation	Temp. ° F	Initial E, psi x 10 ⁻⁶	Yield Strain μ in./in.	Ultimate Strength, σ_t Ksi
0°	RT	30.0	4000	180
0°/90°	RT	16.0	2000	90
90°	RT	3.0	2000	12

(NOTE: For the purpose of this specification, "yield strain" is defined to be the strain at which the particular orientation first becomes inelastic.)

3.5 Identification Marking.— Each roll of prepreg shall be permanently marked with the following data:

SPECIAL INSTRUCTIONS (if required, see 5.2)

RESIN TREATED BORON REINFORCED PREPREG

NR SPECIFICATION NO. ST0130LB0004 TYPE CLASS

WIDTH OF MATERIAL

LINEAR FEET

MANUFACTURER'S BATCH NO. AND DATE OF MANUFACTURE

MANUFACTURER'S DESIGNATION

STORAGE TEMPERATURE, MAX: 0° F

SHELF LIFE: 6 MONTHS at 0° F

INSPECTION RECORD AND COMMENTS: ITEMIZED DESCRIPTION OF REJECTED MATERIAL INCLUDING LINEAR FOOTAGE OF SUCH REJECTS AND THEIR LOCATION.

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4. QUALITY ASSURANCE PROVISIONS

4.1 Responsibility for Inspection.- The supplier shall be responsible for the performance of all inspection requirements specified herein. The supplier may utilize his own facilities or any commercial laboratory acceptable to NR. NR reserves the right to perform or witness any of the inspections specified herein when these inspections are deemed necessary to substantiate prescribed requirements.

4.2 Certificate of Conformance.- The supplier shall furnish with each shipment a certified report (in triplicate), stating conformance to the requirements specified herein and listing the specific results of all the quality conformance inspection tests. This report shall also include this specification number, type and class, the purchase order number, the batch number, roll number and footage in each, manufacturer's designation and date of manufacture. An itemized description of any rejected material including linear footage of such rejects and their location shall also be included.

4.3 Subcontractor.- When materials for subcontract fabrication are purchased directly by the subcontractor, the subcontractor shall be responsible for determining that the material meets all the requirements of this specification. With each part shipment the subcontractor shall submit a copy of the report specified in 4.2.

4.4 Inspection Records.- The supplier's inspection records of examination and tests for conformance to the requirements of this specification shall be kept complete and available to NR upon request.

4.5 Inspection Lot.- A lot shall consist of all the material forming part of one purchase order and submitted for acceptance at one time. A batch shall be that quantity of material compounded and manufactured at one time.

4.5.1 Level of Inspection.- Each batch in each lot shall be tested for conformance to the quality conformance inspection requirements.

4.6 Classification of Inspections.- The inspections requirements specified herein are classified as follows:

1. Qualification Inspection (See 4.7)
2. Quality Conformance Inspection (See 4.8)

4.7 Qualification Tests.- Qualification inspection tests shall be as specified in table V.

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Table V
QUALIFICATION INSPECTION

Test	Requirement paragraph	Method paragraph
<u>Impregnating Resin</u>		
Conformance	3.2.1	4.11
<u>Boron Filament Properties</u>		
Tensile strength	3.2.2	4.12
Modulus of elasticity, tension	3.2.2	4.13
Diameter	3.2.2	4.14
Density	3.2.2	4.15
<u>Glass Fabric Carrier</u>		
Conformance	3.2.3	4.16
<u>Reinforced Uncured Prepreg</u>		
Visual examination	3.3 a,d,e,f	4.17
Filament count	3.3 b	4.18
Filament alignment	3.3 c	4.18
Volatile content	3.3 g	4.19
Resin content	3.3 g	4.20
Tack	3.3 g	4.21
Gel time	3.3 g	4.22
Boron filament spacing	3.3.1	4.23
Boron filament splices	3.3.2	4.24
Allowable width	3.3.3	4.25
Allowable length	3.3.4	4.26
Uniformity	3.3.5	4.27
Storage life	3.3.6	4.28
Workmanship	3.3.7	4.29
<u>Cured Prepreg</u>		
Flexure, longitudinal	3.4	4.30.1
Flexure, transverse	3.4	4.30.2
Horizontal shear	3.4	4.30.3
Tension, sandwich face	3.4	4.30.4

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4.7.1 Regualifications.- Any change in formulation shall be submitted by the manufacturer in writing to the NR Engineering Materials & Producibility via the Purchasing Department. The material shall then be subject to requalification.

4.8 Quality Conformance Tests.- Quality conformance inspection tests shall consist of all tests listed for the reinforced uncured prepreg (see 3.3) and the flexure, transverse flexure and horizontal shear tests listed for the cured prepreg (see 3.4). In addition, the sandwich face tension tests on the cured prepreg may be required if requested by NR Engineering Materials and Producibility.

4.9 Test Conditions.-

4.9.1 Standard Conditions.- Unless otherwise specified herein, all room temperature tests shall be conducted at a temperature of 75° to 79° F, and a relative humidity of 45 to 55 percent.

4.10 Test Specimen Preparation.- Test panels from which test specimens will be prepared shall be fabricated in accordance with ST0105LA0007. Test specimens shall be cut from the test panel prepared, using diamond studded cutters.

4.11 Conformance of the Resin.- The impregnating resin shall be tested for conformance to the applicable requirements of MIL-R-9300.

4.12 Tensile Strength.- The acceptability of boron filament tensile strength for each machine run shall be determined by sample testing in accordance with section C of MIL-STD-414 for an AQL of 10.00. The procedure for evaluating each machine run is to test four samples, compute the average tensile strength (\bar{X}) and the sample range (R) and determine K from $K = (\bar{X} - 377,000)/R$ where X and R are measured in psi. If K is greater than 0.276 then the run is acceptable. If K is less than 0.276, test three more samples and determine K for the seven samples shown above. If K is greater than 0.266 then the run is acceptable. If K is less than 0.266 then test three more samples, compute the average strength (\bar{X}) and the sample range (R) for the new total of ten samples and determine K . In the case of ten samples (R) is the average range of two subgroup ranges of five samples each as described in Standard MIL-STD-414. If K is greater than 0.341 the run is acceptable and if K is less than 0.341 the run is not acceptable.

4.12.1 Strain Rate.- Tensile values shall be determined using a one-inch gage length and a crosshead loading speed of 0.05 in./minute.

4.13 Modulus of Elasticity, Tension.- The tension modulus of elasticity of the boron filaments shall be based either on sonic measurements or specimens using long gage lengths (ten inches or greater) from which the stress-strain values can be obtained. The modulus of elasticity shall be determined for a minimum of one test at the end of each machine run.

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4.14 Filament Diameter.— The diameter of the boron filaments shall be measured by the use of either a micrometer or an optical comparator.

4.15 Filament Density.— The density of the boron filaments shall be determined in accordance with Federal Test Method Std. No. 406, Method 5012.

4.16 Conformance of the Glass Fabric.— The glass fabric carrier shall conform to the requirements of ASTM D579 for type 58 woven glass fabric.

4.17 Visual Examination of the Uncured Prepreg.— The reinforced uncured pre-impregnated materials shall be examined visually, using magnification if necessary in accordance with 3.3.

4.18 Boron Filament Count and Alignment.— The uncured prepreg shall be examined visually using an optical comparator at 50-100X magnification to make the count of the boron filaments. The alignment shall be checked using the optical comparator or other suitable instrument.

4.19 Volatile Content.— A 3 x 3 inch square of 1 ply uncured prepreg shall be weighed to the nearest 0.001 gram (W_1) and heated in an air circulating oven for 14 to 16 minutes at 320° to 330° F. The specimen is then removed, cooled in a desiccator to ambient conditions and reweighed to the nearest 0.001 gram (W_2). The volatile content in percent shall be $100(W_1 - W_2)/W_1$. The mean percent volatile content shall be based on the average of three specimens.

4.20 Resin Content.— The resin content of each roll of the uncured prepreg shall be determined in accordance with the procedure of SPI-Prepreg-1, by boiling in methyl ethyl ketone for 6 minutes. The specimen shall be 3 x 3 inch square of 1 ply uncured prepreg.

4.21 Tack.— The tack shall be determined on a 1 ply 3 x 4 inch specimen of uncured prepreg. With the packaging separator sheet up, place the prepreg on a 0.125 x 4 x 8 inch stainless steel plate, held vertically, having a smooth surface (100 RMS max.). Remove air bubbles and wrinkles with a squeegee. Remove the separator sheet. The prepreg shall not be dislocated by its own weight, but shall be capable of removal without loss of more than 5 percent of the initial weight.

4.22 Gel Time.— The gel time requirements and test method shall be added to this specification in the future.

4.23 Boron Filament Spacing.— The boron filament spacing shall be measured using an optical comparator at 50-100X magnification.

4.24 Boron Filament Splices.— The conformance with the requirements of 3.3.2 for the boron filament splices shall be certified by the supplier on each shipment.

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4.25 Allowable Width.- The width of the prepreg shall be measured using an optical comparator.

4.26 Allowable Length.- The allowable length shall be obtained from the data obtained from the supplier for each roll of prepreg.

4.27 Uniformity.- The uniformity shall be determined visually or by other means at the time of use.

4.28 Storage Life.- The storage life of the uncured prepreg shall be certified by the supplier.

4.29 Workmanship.- The workmanship shall be determined visually or by other means at the time of use.

4.30 Preparation of Cured, Composite Laminated Test Specimens.- The test specimens of cured, composite laminate shall be fabricated in accordance with ST0105LA0007 unless otherwise specified. All filament orientation within the length of the specimen shall be within $\pm 1/2^\circ$. A mean value for strength, based on three specimens, both at room temperature and one elevated temperature (350° F), shall be reported. (NOTE: Strength tests at 270° F, may be required if included on the purchase order.)

4.30.1 Flexure, Longitudinal (0°).-

- Specimen dimensions shall be as shown in figure 1. The thickness dimension (t) will be in the range .0775 - .082. A variation in thickness over a specimen may not exceed 0.004 inch. (NOTE: 15 plies including balance ply of 104 glass.)
- A load support method shall be utilized as shown in figure 1.
- The specimen shall be loaded in a universal test machine at a load rate of 0.05 inch per minute.

d. Record the load at failure.

e. Calculations: Flexure, ultimate, $f_u = \frac{3 PS}{2 Wt^2}$

P = load in pounds

S = span in inches

W = specimen width in inches

t = specimen thickness in inches

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4.30.2 Flexure, transverse (90°).-

- Specimen dimensions shall be as shown in figure 2. The thickness dimension (t) may vary from .0775 to .082. (NOTE: 15 plies including balance ply of 10⁴ glass.)
- A load support method shall be utilized as shown in figure 2.
- The specimen shall be loaded on a universal test machine at a load rate of .05 inch per minute.
- Record the load at failure.

- Calculations: Flexure, ultimate, $f_u = 3PS/4 Wt^2$

P = load in pounds

S = span in inches

W = specimen width in inches

t = specimen thickness in inches

4.30.3 Horizontal Shear.-

- Specimen dimensions shall be as shown in figure 3. Thickness may vary from .0775 to .082. Variation in a specimen shall not exceed 0.003 inch. (NOTE: 15 plies including balance ply of 10⁴ glass.)
- The specimen shall be loaded to failure in a universal test machine at a load of 0.05 inch per minute.
- A load support method shall be utilized as shown in figure 3.
- Record the load at failure.

- Calculations: Horizontal shear, $F_{HS} = 3P/4 Wt$

P = load in pounds

W = specimen width in inches

t = specimen thickness in inches

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4.30.4 Sandwich Face Tension.-

1. Preparation of Test Specimen

A. Prepare boron composite face sheet 1.0 inch wide by 22 inches long with thickness as follows:

- (1) All fibers 0° to 22 inches dimension - 6 plys (0.0306 to 0.0324)
- (2) All fibers 90° to 22 inches dimension - 8 plys (0.0408 to 0.0432)
- (3) Fiber orientation $0^{\circ}/90^{\circ}$ - 8 plys (0.0408 to 0.0432)

Note: $0^{\circ}/90^{\circ}$ skin ply orientation as follows:
 $90^{\circ} - 0^{\circ} - 90^{\circ} - 0^{\circ} - 0^{\circ} - 90^{\circ} - 0^{\circ} - 90^{\circ}$

B. Bond boron composite face sheet into sandwich beams as follows:

- (1) For 0° and $0^{\circ}/90^{\circ}$ composites use
 - (a) 23 lb./ft.³ aluminum honeycomb core 1.5 inches thick by 1.1 inches wide by 22 inches long
 - (b) 0.125 inch thick aluminum sheet same width and length as the boron skin for the opposite face
- (2) For 90° composites use
 - (a) 4.5 lb./ft.³ aluminum honeycomb core 1.5 inches thick by 1.1 inches wide by 22 inches long
 - (b) 0.080 inch thick epoxy/glass fabric laminate same width and length as the boron skin for the opposite face
- (3) Bond using two (2) layers of AF130 or equivalent in both bond lines. Cure at 45 psi for one hour at 350° F.

2. The load support method utilized shall be as shown in Figure 4.

3. The minimum instrumentation for determining elastic properties is shown in Figure 4.

4. The test procedure shall be as follows:

A. Load the specimen to failure at the following load rates:

- (1) 0° -700 pounds per minute.
- (2) $0^{\circ}/90^{\circ}$ -300 pounds per minute.
- (3) 90° -70 pounds per minute.

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B. Record strain gage and load data at the following increments:

- (1) 0°-100 pounds of load.
- (2) 0°/90°-50 pounds of load.
- (3) 90°-10 pounds of load.

C. The strain values from the two longitudinal gages shall not differ more than ten percent and differences less than five percent are attainable.

D. Record the load at failure.

5. The stress in the composite facing is

$$\sigma_t = \frac{4P}{Wt \left[C + \frac{(t + T)}{2} \right]}$$

where σ_t = stress in psi

P = load in pounds

W = width of composite facing in inches

t = thickness of composite facing in inches

C = thickness of core in inches

T = thickness of opposite facing in inches

4.31 Retest.— If a material sample fails to meet the requirements of this specification due to preparation of test specimens, retest is permitted. The results of the original tests and the retest, and the reasons for failure, shall be included in the test report.

4.32 Rejection.— Each batch of material shall be rejected if it does not pass the acceptance tests.

5. PREPARATION FOR DELIVERY

5.1 Packaging.— Prepreg material shall be rolled on a reel of not less than 8 inches in diameter. A non-adherent paper or Mylar separator of a contrasting color shall be used on one side of the material against the glass carrier if used to prevent the layers of material from sticking to each other. Each roll or rolls of prepreg shall be heat sealed in an evacuated, moisture-proof plastic bag. An identification tag shall be placed within each bag prior to sealing.

5.2 Packing.— Units packaged as specified in 5.1 shall be packed in exterior-type shipping containers in a manner that (if refrigerated shipment is required by NR) will allow solid carbon dioxide to be packed in sufficient quantities to maintain a material temperature of 0° F, maximum, during transit. Upon receipt, containers shall be opened and examined to ascertain that solid carbon dioxide remains therein, if used. Prepreg rolls shall be packed in a horizontal position and containers so marked so as to insure horizontal positioning for shipment and later stored in an upright, vertical position. The shipping container

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shall be so constructed so as to assure safe delivery and acceptance at their destination. Shipping containers shall comply with carrier regulations applicable to the mode of transportation.

5.2.1 Marking of Shipment.— Each shipping container shall be marked with the following information:

RESIN TREATED, BORON REINFORCED PREPREG, LOW PRESSURE MOLDING
NR SPECIFICATION NO. ST0130LB0004 TYPE CLASS
NR PURCHASE ORDER NO.
MANUFACTURER'S NAME, TRADEMARK OR SYMBOL

MANUFACTURER'S BATCH AND LOT NO.
STORAGE TEMPERATURE, MAXIMUM 0° F
DATE OF MANUFACTURE
SHELF LIFE: 6 MONTHS AT 0° F

6. NOTES

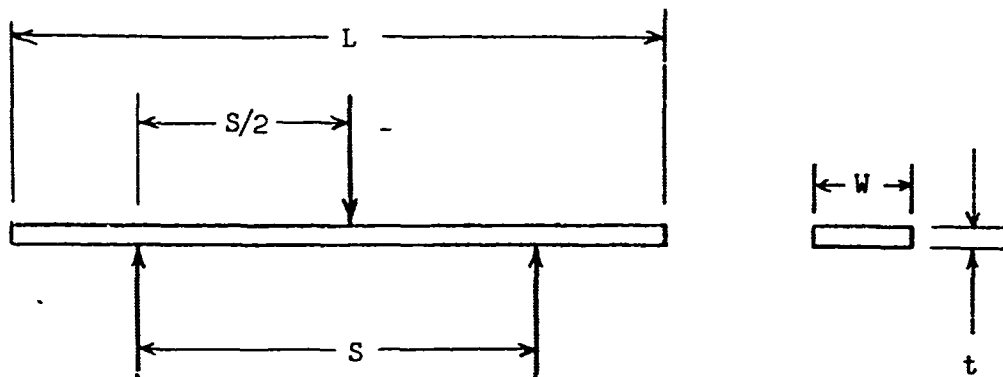
6.1 Intended Use.— The materials procured in accordance with this specification, when molded using low-pressure laminating methods, are suitable for use in air-frame, aerospace and similarly related primary structural components where high stiffness and strength-to-weight ratios are required.

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Longitudinal Flexure (0°)



Length (L) = 4.0
Width (W) = 0.500
Thickness (t) = 0.0775 - 0.082

Span (S) = 2.50

All filaments shall be 0° to the L dimension.

Load and reaction supports shall be $1/8$ " radius steel rod.

All dimensions are in inches.

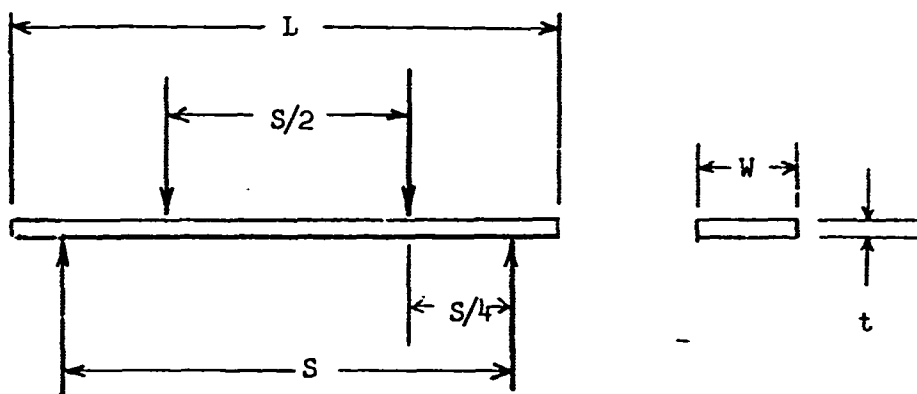
Figure 1. Test Method: Longitudinal Flexure (0°)

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Transverse Flexure (90°)



Length (L) = 3.0 ± 0.1
Width (W) = $0.500 \pm .003$
Thickness (t) = 0.0775 to 0.082

Span (S) = 2.00

Load and reaction supports shall be $1/8''$ radius steel rod.

All filaments shall be 90° to the L dimension.

All dimensions are in inches.

Figure 2. Test Method: Transverse Flexure (90°)

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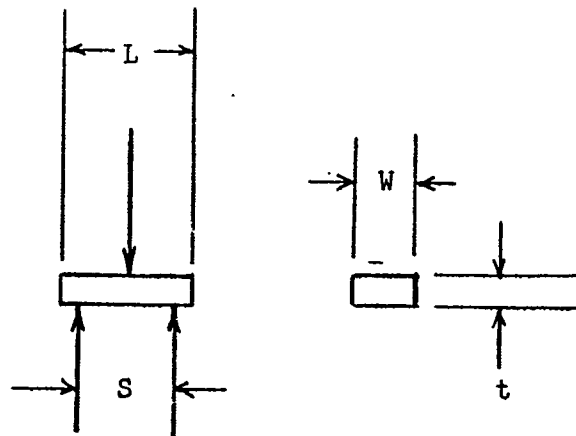
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Horizontal Shear (0°)



Length (L) = 0.60 ± 0.01

Width (W) = 0.250 ± 0.003

Thickness (t) = 0.0775 to 0.082

Span (S) = 0.4 (Overhang must be same over each end.)

Load and reaction supports shall be $1/8$ " radius steel rod.

All filaments to be 0° to the L dimension.

All dimensions are in inches.

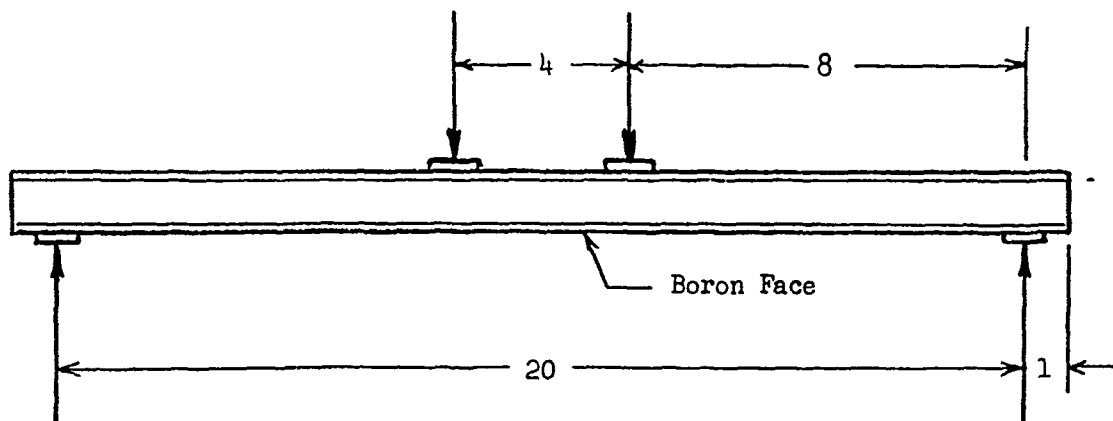
Figure 3. Test Method: Horizontal Shear (0°)

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Sandwich Face Tension



Load Pads - 1.0 wide
Reaction Pads - 1.5 wide
All dimensions are in inches

Instrumentation

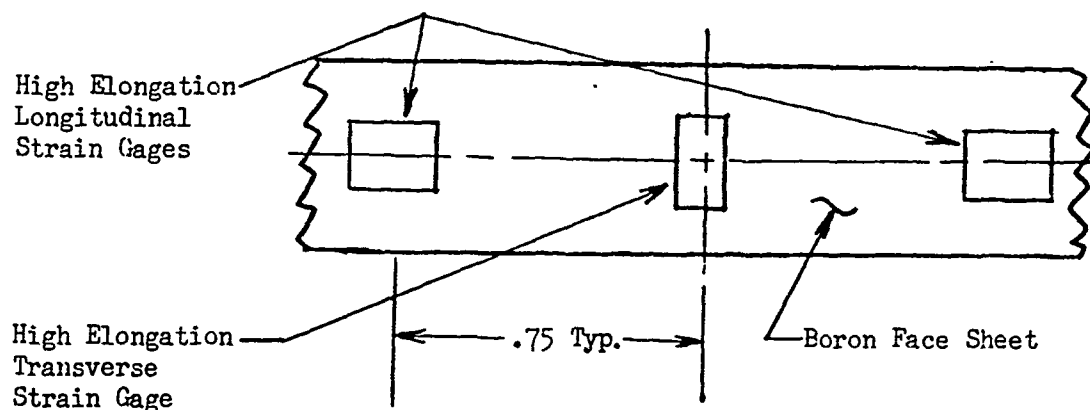


Figure 4. Test Method: Tensile Face Stress In A Sandwich Beam

APPENDIX II

PROCESS SPECIFICATION

ADVANCED COMPOSITES - FABRICATION OF PARTS OR COMPONENTS

UTILIZING BORON/EPOXY PREPREG

(NR Specification ST0105LA0007)

PREPARED BY	CODE IDENT. NO. 43999	NUMBER ST0105LA0007
R. MEADOWS	LOS ANGELES DIVISION	TYPE PROCESS
APPROVALS	NORTH AMERICAN ROCKWELL CORPORATION	DATE 5-7-69
<i>[Signature]</i>	SPECIFICATION	SUPERSEDES SPEC. DATED:
		REV. LTR. PAGE 1 of 8

TITLE **ADVANCED COMPOSITES - FABRICATION OF PARTS OR COMPONENTS UTILIZING BORON-EPOXY PREPREG**

REVISIONS

REV.	DATE	REV. BY	PAGES AFFECTED	REMARKS	APPROVED

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1. SCOPE.- This specification covers the fabrication of parts or components using boron-epoxy preimpregnated materials.

2. APPLICABLE DOCUMENTS

2.1 Documents.- The latest issues of the following documents form a part of this specification to the extent specified herein.

SPECIFICATIONS

North American Rockwell Corporation

STO130LB0004 Advanced Composite Material - Boron Epoxy Prepreg

3. REQUIREMENTS

3.1 Safety.- This specification involves material or operations which are hazardous. Coordinate with Industrial Hygiene and Safety regarding precautionary measures.

3.2 Materials.- Materials shall be as follows:

Acetone	Commercial
Boron-Epoxy Prepreg	STO130LB0004, Type II, Class 1
Coroprene Supports	Armstrong Cork
Glass Fabric	

<u>Designation</u>	<u>Type</u>
104	Impregnated *
120	Dry Commercial
181	Impregnated *
181	Dry Commercial

* Impregnated with the same resin system as the boron fibers.

GS-3 Teflon Release Agent	Ram Chemical, Gardena, California
Methyl ethyl ketone	Commercial
Mylar	E.I. duPont deNemours & Company
Tedlar	E.I. duPont deNemours & Company
Vent Cloth TX1040	Pallflex Products, Putnam, Connecticut

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3.3 Storage of Boron Impregnated Materials.- Boron impregnated materials (ST0130LB0004) shall be stored in sealed plastic bags at temperatures not exceeding 0°F. Before use, the material shall be removed from storage and allowed to come to room temperature before unsealing the plastic bag. A record of the time out of refrigeration shall be maintained and when the accumulated time exceeds 10 days, the material shall be retested in accordance with 4.2. Any partially laid-up parts which must be stored, shall first be sealed in plastic bags before storage at temperatures not exceeding 0°F. Upon removal from storage, the parts shall be allowed to reach room temperature before being unsealed.

3.4 Manufacturing Documents.- Manufacturing personnel shall have all applicable drawings and specifications and be thoroughly familiar with their contents before starting any fabrication. A permanent manufacturing record shall be kept of each batch and roll number of all boron prepreg material, together with the applicable part numbers and individual serial numbers of all parts fabricated with the material.

3.5 Equipment.-

3.5.1 Tooling.- Tooling shall be of steel or titanium. It shall be adequate to manufacture parts which meet all engineering requirements affected by tooling.

3.5.2 Templates.- Templates shall be furnished for each ply of boron prepreg called out on the engineering drawing. The templates shall be of transparent 0.007 inch thick Mylar film and the ply size, location, numerical sequence, and filament orientation shall be clearly and permanently marked. The templates shall be so designed that one surface will make a left-hand and the opposite surface will make a right-hand part. Each surface shall be clearly and permanently marked as to which hand part it makes. The templates shall have tooling pin holes around the periphery in order to locate each ply exactly in relation to the other plies.

3.5.3 Autoclave.- The autoclave shall have vacuum system, thermocouples with recording charts and pressure regulator system. It must be capable of delivering 80 to 90 psi and 340° to ±360°F. The vacuum system must be capable of at least 25 inches of vacuum.

3.5.4 Auxiliary Equipment.- The following auxiliary equipment is required:

- a. Portable vacuum cleaner
- b. Scissors
- c. "Stanley" knives
- d. Boron prepreg tape dispenser, supported overhead in the layup room, with the head able to swivel 360 degrees.
- e. Teflon or polyethylene squeegee (6X3X1/4 inch piece).

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3.6 Template Layup.-- Template layup shall be as follows:

- a. Wipe the exposed template surface with clean cheesecloth moistened in either acetone or methyl ethyl ketone (MEK). Blow dry with clean dry, oil-free air or nitrogen.
- b. A roll of boron prepreg, at room temperature, shall be located on the dispenser.
- c. Unroll sufficient boron prepreg to form one strip across the template. Cut with a sharp tool.
- d. Layup the boron prepreg in the area indicated on the template with the scrim cloth up. Place the 3-inch wide tapes adjacent to each other but do not overlap. Gaps shall not exceed 0.030 inch.
- e. Trim the tape within the maximum/minimum line shown on the template.
- f. Rub out the boron layup with a squeegee to create intimate contact with the template. Rub parallel to the filaments. Do not try to move resin.
- g. Remove all boron splinters, crossovers or other foreign objects from the surface. Use vacuum cleaner, if necessary.

3.7 Template Layup Inspection.-- The template layup shall be inspected as follows:

- a. Gaps between boron filaments shall not exceed 0.030 inch in width whether within a 3 inch wide tape or between tapes.
- b. Boron filaments shall not be stacked one above another or crossover each other within a ply.
- c. The layup shall be free of cured pieces of resin.

NOTE: Should any of the above defects occur, they shall be removed by removing the entire length of filament in a strip wide enough to remove the defect. The strip shall be replaced with acceptable material.

- d. The layup shall be free of all foreign material. Foreign material shall be removed where possible without damage to the layup. If the foreign material cannot be removed without damage, the strip shall be removed and replaced as above.

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3.8 Storage of Template Layup.- Cover the layup with a clear plastic protective film. Store all template layups flat. If the templates are not to be laid up within 24 hours, they shall be stored at temperatures not exceeding 0°F in a sealed bag.

3.9 Preparation of Layup Tool.- Prepare the layup tool as follows:

- a. Clean the tool with clean cheesecloth, using either acetone or MEK to remove all foreign material. Polish to develop a smooth surface. Wipe with a final clean cheesecloth moistened with acetone or MEK and immediately wipe dry with another clean cheesecloth. Blow with clean, dry oil-free air or nitrogen to remove any traces of lint.
- b. Apply GS-3 release agent.
- c. Cover the layup tool with TX-1040 vent cloth or equivalent.

3.10 Lay Up Of Part.- Lay up the part as follows:

- a. Lay up onto the tool a peel ply if specified by the engineering drawing. The peel ply shall consist on one ply of 181 glass fabric epoxy prepreg (impregnated with the same resin system as the boron fibers) with 1/2 inch excess on all sides. Rub out with a squeegee to remove all air pockets and wrinkles. All splices shall be the butt type. Remove the separator film.
- b. Select the required template and place it on the tool with the boron layup down.
- c. Locate one side of the template on the correct tool pins. Caution shall be used to locate the template on the correct pins.
- d. Remove any protective film from between the tool and boron layup. Do not force the film. Do not disarrange any filaments.
- e. Work the lay up against the tool or peel ply using a wiping motion to create an intimate contact between the boron and the tool or peel ply.
- f. Remove the template, using a peeling action created by rolling the template parallel to the filaments into a 2 inch diameter roll, vibrating the template as it is rolled. Dry ice shall not be used to facilitate template removal.
- g. Inspect the boron layup after the template removal in accordance with 3.7.
- h. Repeat steps b through g until all of the required plies are laid up. Each ply layup shall be inspected by Quality Assurance before the next ply is started.
- i. The external surface of the part shall consist of one balance ply of 104 glass fabric impregnated with the same resin system as the boron fibers and cured with the part.

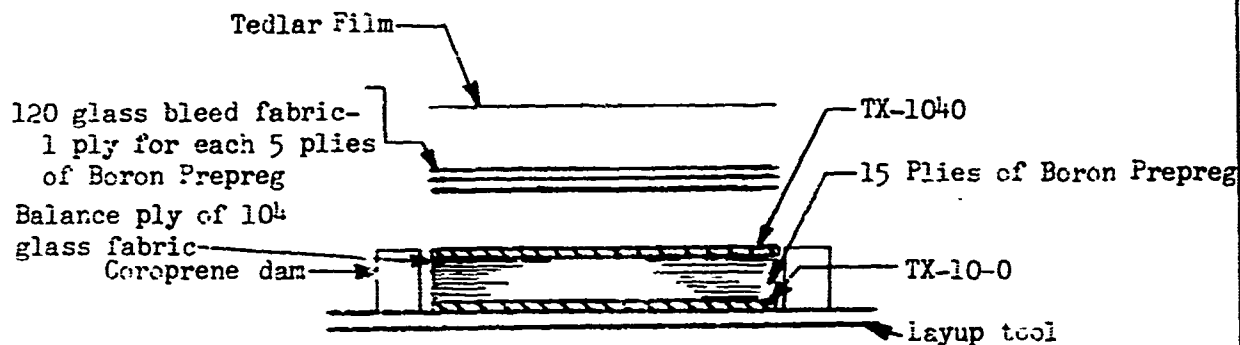
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3.11 Preparation for Cure.- The preparation for cure shall be as follows:

- a. Cover the part with TX-1040 vent cloth or equivalent. The vent cloth shall be the same size as the part and shall not extend beyond the periphery of the part.
- b. Locate 1 inch wide boundary supports of the required thickness, made from Coroprene, or equivalent, within 0.060 inch of the part edge to prevent filament washing during resin flow. The boundary supports must be at least 0.03 inch thicker than the total lay-up thickness (based on 0.006 inch thickness per ply). The support material must have a minimum of 25 percent compressibility at 100 psi. Gaps in the boundary support shall be filled to prevent the loss of resin.
- c. Layup of 1 ply of dry 120 glass fabric for each 5 plies of boron prepreg. The 120 glass should be the same size as the part and shall not extend beyond the periphery of the part.
- d. Place a layer of Tedlar or equivalent, over the entire layup so that the edges extend well beyond the periphery of the part. For the escape of air from the controlled-flow bleed system described above, place holes in the plastic film approximately the size of a pencil lead. Start these holes 1/2 inch from one edge and place holes on 2 inch centers.
- e. Cover the entire layup with 2 plies of dry 131 glass fabric.
- f. The entire layup shall be held securely against the tool by vacuum during all subsequent handling until the part is in the autoclave for cure.
- j. The controlled-flow bleeder system is illustrated by the following sketch:



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3.12 Cure.-- The assembled layup shall be placed in an autoclave, and the temperature of the autoclave shall be raised to 350°F in 30 minutes or less at a rate that does not exceed 10°F per minute. Parts shall be cured at 80 to 90 psi and a temperature of 340 to 360°F as follows:

- a. Parts fabricated with Narmco 5505 Rigidite shall be cured for 110 to 130 minutes. With full bonding pressure maintained the parts shall then be cooled below 150°F as measured at the hottest area of the part.
- b. Parts fabricated with Minnesota Mining and Manufacturing SP-272 shall be cured for 55 to 65 minutes. With full bonding pressure maintained, the parts shall then be cooled below 150°F as measured at the hottest area of the part. The part shall be postcured for 215 to 265 minutes at 340° to 360°F. (An oven may be used for the postcure; parts shall be heated at a rate not to exceed 10°F per minute).
- c. The cure of parts fabricated from ST0130LB004, Types I and III, boron epoxy prepreg shall be as specified by Materials and Producibility Engineering.

3.13 Test Tabs.-- Test tabs fabricated with the production parts and the physical tests on the tabs shall be as specified by Materials and Producibility Engineering.

3.14 Nondestructive Testing.-- Nondestructive testing of parts shall be as required by Materials and Producibility Engineering.

3.15 Finished Parts.-- All finished parts shall meet the following requirements.

- a. Before trimming, the part shall be inspected in an excess area with a Barcol Impressor. The average of ten readings shall be not less than 80.
- b. The thickness shall not be less than 0.0051 inch nor greater than 0.0054 inch per ply.
- c. After trimming, the part shall be weighed to within 1/10 pound and the weight recorded on the planning sheet.

3.16 Packaging.-- The parts shall be wrapped in clean heavy paper or plastic sheet, sealed, and labeled with the part number or other suitable identification. The wrapped parts shall be packed in suitable containers to prevent damage to the part.

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4. QUALITY ASSURANCE PROVISIONS

4.1 Surveillance.- Quality Assurance shall establish the minimum surveillance, control, and maintenance required to assure continued quality and consistency in manufacture.

4.2 Retest of Boron Impregnated Materials.- Boron impregnated materials which require retest shall meet the qualification inspection requirements for cured prepreg in accordance with ST0130LB0004. (See 3.3.)

4.3 Inprocess Layup Inspection.- Inprocess layup inspection shall be made by Quality Assurance in accordance with 3.7, and 3.10 g and h.

4.4 Visual Inspection.- All parts shall be visually inspected to insure compliance with section 3. The cured part shall be closely observed on both surfaces and all items not acceptable shall be recorded on the planning sheet. The following are not acceptable.

- a. Gaps between boron filaments in excess of 0.030 inch in width.
- b. Boron filaments crossing over an adjacent filament.
- c. Wrinkles.
- d. Foreign objects such as metal chips and loose, short fibers.
- e. Contour discrepancies.

4.5 Determination of Part Thickness.- The part shall be marked in a suitable grid pattern and measured for thickness. The thickness at each grid intersection shall be recorded on the planning sheet and accepted by Quality Assurance if within the design limits. The thickness shall be in accordance with 3.15.

5. PREPARATION FOR DELIVERY.- Not applicable.

6. NOTES.- Not applicable.

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13. ABSTRACT <p>This volume summarizes that portion of the program concerned with the development of a material processing technology at NR, the determination of material properties for a specific epoxy resin and glass scrim cloth, the determination of the effects of nuclear blast on the strength of a composite laminate, and the assessment of existing micromechanics techniques for the prediction of composite lamina characteristics. All efforts in this program were relative to a specific boron/epoxy composite material system known commercially as Narmco Rigidite 5505. A procurement and a process specification were established during the program and have demonstrated a capability to produce satisfactory material consistently. Tests are described for a program to characterize separately Narmco 2387 resin and 104 glass scrim cloth. Test data are presented for standard mechanical properties and elastic constants at both room temperature and 350°F. A test program to determine the effects of nuclear blast on boron/epoxy laminates is described and test data are presented. An evaluation is presented to show the degree of validity of several micromechanics techniques for predicting composite lamina characteristics from known properties of the constituents.</p>			

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Filamentary Composite Structure

Fiber-reinforced Materials

Filamentary Laminates

Composite Material

Composite Structure

Boron/Epoxy Composite

Narmco 5505 (Rigidite)

Epoxy Resin Matrix

Narmco 2387 Resin

Boron Filament

Glass Scrim Cloth

Anisotropic Analysis

Micromechanics

Strength Properties of Composites

Elastic Constants of Composites